NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

RESONANT ACOUSTIC DETERMINATION
OF
COMPLEX ELASTIC MODULI

by

Tan, Beng Hock

March 1991

Thesis Advisor: Steven L. Garrett
Co-Advisor: David A. Brown

Unclassified

Security Classification of this page

REPORT DOCUMENTATION PAGE

1a Report Security Classification Unclassified	1b Restrictive Markings
2a Security Classification Authority	3 Distribution Availability of Report
2b Declassification/Downgrading Schedule	Approved for public release; distribution is unlimited.
4 Performing Organization Report Number(s)	5 Monitoring Organization Report Number(s)
6a Name of Performing Organization Naval Postgraduate School; 6b Office Symbol *(If Applicable)* 33	7a Name of Monitoring Organization Naval Postgraduate School
6c Address *(city, state, and ZIP code)* Monterey, CA 93943-5000	7b Address *(city, state, and ZIP code)* Monterey, CA 93943-5000
8a Name of Funding/Sponsoring Organization Naval Sea System Command; 8b Office Symbol *(If Applicable)* 06UR	9 Procurement Instrument Identification Number
8c Address *(city, state, and ZIP code)* Washington, D.C. 20362-5101	10 Source of Funding Numbers: Program Element Number; Project No; Task No; Work Unit Accession No

11 Title *(Include Security Classification)* RESONANT ACOUSTIC DETERMINATION OF COMPLEX ELASTIC MODULI (Unclassified)

12 Personal Author(s) Tan, Beng Hock

13a Type of Report	13b Time Covered	14 Date of Report *(year, month,day)*	15 Page Count
Master's Thesis	From To	March 1991	136

16 Supplementary Notation The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17 Cosati Codes			18 Subject Terms *(continue on reverse if necessary and identify by block number)*
Field	Group	Subgroup	Viscoelaticity, complex modulus, viscoelastic transition.

19 Abstract *(continue on reverse if necessary and identify by block number*

An acoustic resonance based technique using a free-free bar has been extended to investigate the complex (storage and loss) moduli of non-magnetic materials having circular cross section. Using this technique, the bar can be selectively excited in three independent vibrational modes, *i.e.*, torsional, flexural, and longitudinal modes. The torsional mode yields the shear modulus. Either the flexural or longitudinal modes can be used to obtain Young's modulus. These resonant modes can be tracked continuously by means of a phase-locked-loop (PLL) as the temperature (and resonant frequency) of the rod is changed. The in-phase amplitude of the receiver output of the electrodynamic transducer is proportional to the quality factor, Q, of the material. It can be used to continuously track the loss tangent ($= 1/Q$) of the material as a function of temperature and frequency. Results for complex shear modulus and Young's modulus were obtained for a castable epoxy type PR1592 and complex shear modulus for polymethyl methacrylate (PMMA) and Uralite 3130. Over the temperature and frequency range that was accessible, a clear viscoelastic transition was observed in both the storage modulus and loss tangent curves of PR1592.

20 Distribution/Availability of Abstract	21 Abstract Security Classification
[X] unclassified/unlimited [ ] same as report [ ] DTIC users	Unclassified

22a Name of Responsible Individual	22b Telephone *(Include Area code)*	22c Office Symbol
Steven L. Garrett	(408) 646-3431	PH/Gx

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted — security classification of this page

All other editions are obsolete — Unclassified

Approved for public release; distribution is unlimited.

Resonant Acoustic Determination of Complex Elastic Moduli

by

Tan, Beng Hock
Civilian, Singapore Ministry of Defence
B.Eng(Mech), National University of Singapore, 1981

Submitted in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
March 1991

Karlheinz E. Woehler, Chairman
Department of Physics

ABSTRACT

An acoustic resonance based technique using a free-free bar has been extended to investigate the complex (storage and loss) moduli of non-magnetic materials having circular cross section. Using this technique, the bar can be selectively excited in three independent vibrational modes, *i.e.*, torsional, flexural, and longitudinal modes. The torsional mode yields the shear modulus. Either the flexural or longitudinal mode can be used to obtain Young's modulus. These resonant modes can be tracked continuously by means of a phase-locked-loop (PLL) as the temperature (and resonant frequency) of the rod is changed. The in-phase amplitude of the receiver output of the electrodynamic transducer is proportional to the quality factor, Q, of the material. It can be used to continuously track the loss tangent ($= 1/Q$) of the material as a function of temperature and frequency. Results for complex shear modulus and Young's modulus were obtained for a castable epoxy type PR1592 and complex shear modulus for polymethyl methacrylate (PMMA) and Uralite 3130. Over the temperature and frequency range that was accessible, a clear viscoelastic transition was observed in both the storage modulus and loss tangent curves of PR1592.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a_n	=	coefficient of polynomial function
a_T	=	temperature-frequency shift factor
b	=	loss tangent empirical constant
c_F	=	phase speed of flexural wave
c_L	=	phase speed of longitudinal wave
c_T	=	phase speed of torsional wave
d	=	diameter of rod
f	=	resonance frequency
f_n^F	=	normal mode frequency of flexural vibration
f_n^L	=	normal mode frequency of longitudinal vibration
f_n^T	=	normal mode frequency of torsional vibration
Δf	=	-3 dB bandwidth
k, k_1, k_2	=	spring constant of material
k^*	=	complex spring constant
k'	=	real part of complex spring constant
k''	=	imaginary part of complex spring constant
m	=	mass of rod
n	=	mode number
u	=	speed of vibration at the ends of rod
z	=	distance from neutral axis
A	=	constant of proportionality
B	=	magnetic field magnitude
E	=	Young's modulus

E_{st} = energy stored

E_d = average rate of energy dissipation

F = force

G = shear modulus

G^* = complex shear modulus

G' = shear storage modulus

G'' = shear loss modulus

I = electrical current

L = length of rod or effective length of coil

N = number of turns of coil

Q = quality factor

R, R_2 = mechanical resistance

S = cross-sectional area of rod

T = temperature

T_s = standard reference temperature for WLF equation

V_{in} = in-phase output voltage of lock-in amplifier

δ = phase angle between stress and strain

ϕ = angular displacement

λ = wavelength

κ = radius of gyration

ρ = mass density

σ = Poisson's ratio, or standard deviation

τ = relaxation time constant

ω = angular frequency

ξ = linear displacement

ACKNOWLEDGEMENTS

I owe the completion of this work to many friends and colleagues, and my special thanks go to Professor Steven L. Garrett and David A. Brown for their guidance, patience, inspiration and enthusiasm which kept me going. I would like to thank Professor Steven R. Baker and Professor Oscar B. Wilson for their advise and use of their facilities; Glenn Harrell for making possible my experimental tests through his construction of the test jig and George Jaksha for his technical support.

My thanks also to my friends, Yee Kah Chee, Lee Yeaw Lip, Ng Kok Chuan and David Lim for their invaluable help as my computer advisors. A special tribute to my wife, Su Yng and my daughter, Ying Xiang for their love, support and understanding.

Last but not least, my heart felt thanks to God for giving me this opportunity to work with such wonderful people and for seeing me and my family through the entire postgraduate course.

This work was supported by the Naval Sea Systems Command, and the Naval Postgraduate School Research Program.

I. INTRODUCTION

A. MOTIVATION

It is important that the mechanical properties of elastomeric or rubber-like materials be accurately measured and their dependence on temperature, static pressure and other ambient parameters be determined for many fields of science and engineering. These rubber-like materials are being used in various applications such as materials for anti-vibration mounting, hydrophone designs and other acoustics applications. It is known that the static and dynamic moduli of plastics can differ substantially [Ref. 1] and in many situations, it is the dynamic moduli that are the appropriate moduli which determine the quantity of interest such as the dissipative characteristics of vibration isolation material, the resonant frequencies of a linear mechanical system and the sensitivity of many transduction mechanisms.

For most applications, the elastic moduli at the frequencies of intended operations are of interest rather than the static modulus. Nevertheless, manufacturers' specifications for elastic constants of castable polymers are not particularly useful as they are usually determined by static techniques and rarely contain more than one modulus if available. For an isotropic, homogeneous material, all the elastic properties can be completely characterized by just two moduli. Therefore, development of a technique that can accurately determine these dynamic properties is essential for applications engineers and designers and is the topic of this research.

B. TECHNIQUE

In general, the dynamic moduli of a material can be determined by forced vibration test methods. That is, directly measuring the force and resulting displacement or acceleration and using Hooke's law. These can be broadly classified as resonant and non-resonant methods, each method having its advantages and disadvantages [Ref. 2]. Resonant based techniques have the advantage of higher signal-to-noise ratio because at resonance, the response of the sample is quality factor, Q, times higher than the response off resonance. This is an important consideration with a high loss material. Further, as the fundamental measurement is frequency, this suggests that one can obtain extremely high precision with a relatively inexpensive instrument such as a frequency counter. The resonant technique used in this research has been described and discussed in detail in a paper written by Garrett [Ref. 3], using a transducer consisting of coils of magnet wire placed in the magnetic field created by a pair of permanent magnets. Using identical transducers for driver and receiver (pick-up), it is able to selectively excite a single rod-shaped sample of circular or elliptical cross-section into torsional, flexural and longitudinal resonant modes. After obtaining the resonant frequency, knowing the mass density, ρ , and dimensions of the sample, the storage modulus can be obtained from the fact that the bar resonance is proportional to the appropriate wave speed. The complex moduli of the rubber-like material can be obtained together with the measurement of the quality factor, Q , or the free decay time, τ . A commercially available device can be obtained from Reference 4.

C. HISTORY

The resonant bar technique, as it will be called from now onward, is a refinement of one developed by Barone and Giacomini [Ref. 5] to study the modes of vibration of bars of different cross sections. It was used as a teaching laboratory experiment at University of California Los Angeles by Professor Isadore Rudnick and currently, it is being used in acoustic laboratory courses at Naval Postgraduate School to demonstrate modes of bar, and recently, by Wetterskog, Beaton and Serocki [Ref. 6], to determine the dynamic moduli and their temperature dependence for numerous sample of materials for fiber-optic hydrophone applications. Improvements to the resonant bar technique and continuous resonance tracking to yield both storage and loss moduli as a function of temperature and frequency are described in this thesis.

II. THEORY

A. DYNAMIC MODULI DETERMINATION

A uniform, isotropic, cylindrical rod of a homogeneous solid with a diameter, d, and length L, with $L > \lambda >> d$, so that radial motion can be neglected, will propagate three independent waves. These modes will exhibit resonances at appropriate frequencies, depending on the boundary conditions imposed on the ends of the rod. Applying the boundary conditions to a slender rod with unrestricted ends, *i.e.*, free-free boundary conditions, the solutions to the resonant modes can be obtained [Ref. 7: pp. 57-76, Ref. 3].

1. Non-dispersive Modes

The displacement, ξ, and angular displacement, ϕ, associated with the longitudinal and torsional modes satisfy an ordinary second-order wave equation [Ref. 8 : pp.94, 112]. For a free-free boundary condition, the resonances are harmonically related and correspond to an integral number of half-wavelength contained within the length of the rod. It should be noted that the assumed boundary condition does not take the added mass of the transducers and their adhesive into account. Nevertheless, the effect is not ordinarily significant since the additional mass is rarely more than a few percent of the mass of the rod.

a. Longitudinal Vibration - Dynamic Young's Modulus

The phase speed of the longitudinal waves, c_L, is given by Young's modulus, E, and the mass density, ρ [Ref. 7 : p. 59]

$$c_L = \sqrt{\frac{E}{\rho}} \,. \tag{1}$$

The normal-mode frequencies of the bar are then given by

$$f_n^L = \frac{n c_L}{2L} \,; \quad n = 1,2,3,... \,, \tag{2}$$

where n is the mode number of the vibration corresponding to the number of nodes in the standing wave. When the wavelength, λ, begins to become comparable with the lateral dimension of the bar, the assumption of slenderness fails and the normal-mode frequencies deviate increasingly from a harmonic progression. Nevertheless, for a slender rod, these two equations can be used to solve for Young's modulus of the bar

$$E = 4\rho L^2 \left(\frac{f_n^L}{n}\right)^2 . \tag{3}$$

b. Torsional Vibration - Dynamic Shear Modulus

For a cylindrical rod, the phase speed for the torsional waves, c_T, is given by the shear modulus, G, and the mass density, ρ [Ref. 8 : p.11]

$$c_T = \sqrt{\frac{G}{\rho}} \,. \tag{4}$$

If the rod was elliptical, with major and minor radii, a and b, respectively, the speed is modified by the multiplicative factor [$2ab \,/\, (a^2 + b^2)$] [Ref. 9]. Applying the free-free boundary condition leads to a series of harmonic modes with frequencies given by

$$f_n^T = \frac{n c_T}{2L} \,; \quad n = 1,2,3,... \,. \tag{5}$$

These two equations can be used to solve for the shear modulus of the bar

$$G = 4\rho L^2 \left(\frac{f_n^T}{n}\right)^2, \qquad (6)$$

where n is again the mode number of the vibration. By obtaining the resonance frequency of both the torsional and longitudinal modes of a homogeneous, isotropic rod of known mass and dimensions, the complete set of elastic constants (*i.e.*, bulk modulus, Poisson's ratio, *etc.*) can be determined as only two independent moduli are required to completely characterize such a system.

2. Dispersive Mode - Flexural Mode

The flexural phase speed, c_F, is given as [Ref. 7 : p. 71]

$$c_F = \sqrt{2\pi f \kappa c_L}, \qquad (7)$$

where κ is the radius of gyration given by [Ref. 7 : p.69]

$$\kappa^2 = \left(\frac{1}{S}\right)\int z^2 \, dS, \qquad (8)$$

where S is the cross-sectional area of the rod, and z is the distance of an element above the neutral axis in the direction of flexure. Therefore the flexural wave phase speed varies with the square root of the frequency. A slender rod thus exhibits dispersion for flexural mode. The application of free-free boundary condition gives a series of modes that are not harmonic. The frequency of the nth overtone, f_n^F, is given by [Ref. 7 : p. 75]

$$f_n^F = \frac{\pi n^2 c_L \kappa}{8L^2}; \; n = 3.0112, 4.9994, 7, 9, 11..., \qquad (9)$$

for a rod of circular cross-section, $\kappa = d/4$, where d is the diameter of the rod. Solving the above equations to obtain Young's modulus

$$E = \frac{1024}{\pi^2}\frac{\rho L^4}{d^2}\left(\frac{f_n^F}{n^2}\right)^2; \; n = 3.0112, 4.9994, 7... . \qquad (10)$$

B. VISCOELASTIC MODEL OF SOLID

1. Viscoelasticity

Many solids exhibit primarily elastic effects when subjected to low levels of strain and obey Hooke's law. Under a low amplitude dynamic force, there is a corresponding deformation such that in the linear limit, the resulting strain is proportional to the magnitude and in-phase with the applied stress. The imparted energy is recoverable and not dissipated as heat. The ratio of the applied stress to the resulting normalized deformation or strain is equal to the elastic modulus. The modulus of these materials may be independent of frequency over a large range of frequencies. On the other hand, many liquids show appreciable viscous effects. The stress and strain are always 90° out-of-phase under infinitesimal rates of strain, and all of the shear energy transferred to the liquid is dissipated as heat. If the properties of a material fall between an ideal Hookean solid and an ideal Newtonian fluid, which is the case for most polymers, when a dynamic stress is applied, some of the energy input will be stored and some of the energy input will be dissipated. The material may recover part of its deformation when the stress is removed. Under sinusoidal oscillating stress, the strain is neither exactly in-phase with the applied stress nor 90° out-of-phase but it is somewhere in between. Materials whose behavior show such characteristics are called viscoelastic.

2. Simple Mechanical Model

The simplest mechanical model of a viscoelastic system is one spring (elastic) and one dashpot (viscous), either in series or in parallel [Ref. 10 : pp. 16-18]. A series element is called a Maxwell element and a parallel element is called a Voigt element. Nevertheless, a combination of these elements are needed to accurately represent the viscoelastic properties of a material.

For a Voigt element, the force, F, can be written in terms of the viscous element, R, the elastic element, k, and the displacement, ξ, as

$$F = (k + j\omega R)\,\xi, \tag{11}$$

where, $j = \sqrt{-1}$, hence, the equivalent complex modulus can be represented as

$$k^* = k + j\omega R, \tag{12}$$

which has a real part and imaginary part and a relaxation time constant, τ, and a phase angle, δ, given by

$$\tau = \frac{R}{k}, \tag{13}$$

$$\delta = tan^{-1}\left(\frac{\omega R}{k}\right). \tag{14}$$

In this simple model, the real component is independent of frequency, but it may be a function of temperature. The imaginary part is definitely a function of frequency and it increases without bound with increasing frequency. Obviously, this model is inadequate to accurately describe the behavior of a viscoelastic material under dynamic stress.

By adding an elastic element in parallel with a Maxwell model, as in Figure 1(a), which has a equivalent circuit as shown in Figure 1(b), the equivalent impedance can be expressed as

$$Z = \frac{F}{u} = \frac{k_1}{j\omega} + \frac{R_2 k_2}{k_2 + j\omega R_2}, \tag{15}$$

where u is the velocity equal to $d\xi/dt$. Then the dynamic force can be written as

$$F = Zu$$

$$= \left(\frac{k_1}{j\omega} + \frac{R_2 k_2}{k_2 + j\omega R_2}\right) j\omega\xi$$

$$= \left(k_1 + \frac{\omega^2 R_2^2 k_2}{k_2^2 + (\omega R_2)^2} + j\frac{\omega R_2 k_2^2}{k_2^2 + (\omega R_2)^2}\right)\xi. \tag{16}$$

Hence the equivalent complex modulus is

$$k^* = k_1 + \frac{\omega^2 R_2^2 k_2}{k_2^2 + (\omega R_2)^2} + j\frac{\omega R_2 k_2^2}{k_2^2 + (\omega R_2)^2}. \tag{17}$$

From this expression, it can be seen that the real part and the imaginary part depend on frequency, and if R_2 / k_2 is a function of temperature, k^* depends on temperature also. The frequency dependence of k' (real part of k^*) and k'' (imaginary part of k^*) is shown in Figure 2. Other similar models can be found in Bland [Ref. 11 : pp.114-115].

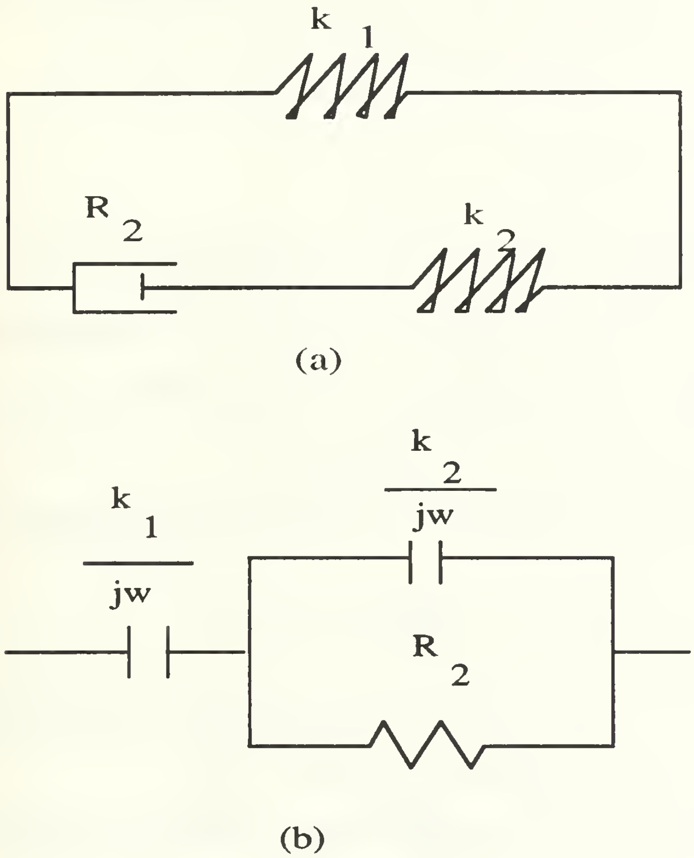


Figure 1. The simple viscoelastic model :
(a). The mechanical equivalent circuit.
(b). The electrical equivalent circuit.

This model, with a single relaxation time constant, is similar in approach to that applied by Rudnick in describing the low temperature liquid ^3He [Ref. 12]. Using this model, some preliminary calculations were done. Nevertheless, as it has been stated above, the results for polymeric elastomers deviate substantially. This can be expected as the behavior of the viscoelastic polymeric material is far more complex than this simple single relaxation time model can fully describe.

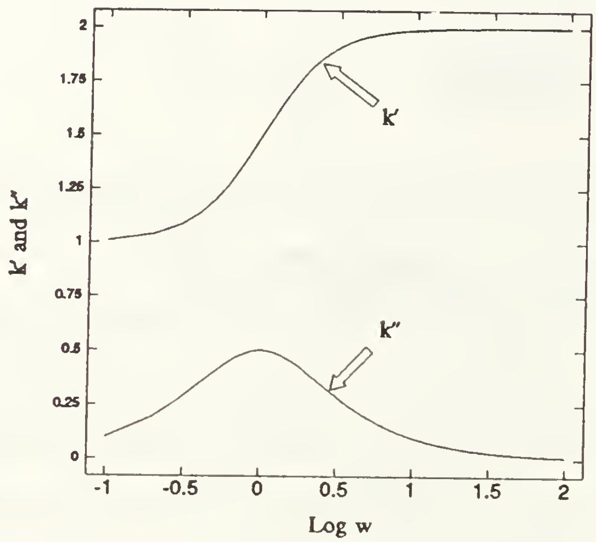


Figure 2. Frequency dependence of k' and k''

3. Complex Modulus, Loss Tangent and Quality Factor

In a dynamic measurement, the characteristic elastic modulus of a viscoelastic material can be represented as a complex quantity, G^*, [Ref. 10 : p.32]

$$G^* = G' + jG'', \tag{18}$$

$$\tan\delta \equiv \frac{G''}{G'}. \tag{19}$$

The storage modulus, G', is defined as the stress in-phase with the strain in a sinusoidal shear deformation divided by the strain. It is a measure of the energy stored and recovered per cycle.

The loss modulus, G'', is defined as the stress 90° out-of-phase with the strain divided by the strain. It is a measure of the energy dissipated or lost as heat per cycle of sinusoidal deformation.

The loss tangent , $\tan\delta$, is thus a measure of the ratio of energy lost to energy stored in a cyclic deformation process. It is also equal to the reciprocal of quality factor, Q.

The quality factor of a system can be defined by [Ref. 7 : p.16]

$$Q = \frac{f}{\Delta f}, \tag{20}$$

where f is the resonant frequency and Δf is the full bandwidth over which the average power has dropped to one-half its resonance value. In terms of relaxation time of the system, τ, the quality factor can be expressed as [Ref. 7 : p.16]

$$Q = \pi f \tau, \tag{21}$$

or in a simple harmonic oscillator, as a function of mass, m, and mechanical resistance, R, as

$$Q = \frac{2\pi f m}{R}. \tag{22}$$

The quality factor can also be expressed as [Ref. 13]

$$Q = \frac{2\pi f E_{st}}{E_d}, \tag{23}$$

where E_{st} is the energy stored in the resonance and E_d is the average rate of energy dissipation.

If u is the speed of the vibration, F is the amplitude of the constant applied force and m is the mass, at resonance,

$$u = \frac{F}{R}, \tag{24}$$

and thus,

$$R = \frac{F}{u}, \tag{25}$$

combining equations (22) and (25), we arrive at

$$Q = Afu, \tag{26}$$

where A is a constant of proportionality

$$A = \frac{2\pi m}{F}, \tag{27}$$

and hence,

$$\frac{Q}{fu} = A. \tag{28}$$

4. Dynamic Behavior of Viscoelastic Material

From equation (17), the storage modulus, k', can be expressed as

$$k' = k_1 + \frac{\omega^2 R_2^2 k_2}{k_2^2 + (\omega R_2)^2}. \tag{29}$$

As $\omega \to 0$, $k' \to k_1$, and as $\omega \to \infty$, $k' \to k_1 + k_2$. As stress is applied at low frequency, the delayed response of the material occurs within the period of the stress reversal. Near equilibrium is achieved at all time. However, as the frequency of the applied stress increases, a point will be reached when the response of the material cannot "keep up" with the stress and its deformation reduces. Consequently, as the frequency of applied stress increases, the storage modulus increases substantially. Moreover, energy loss, which can be measured by the phase angle between the stress and strain (or the loss tangent), behaves differently. At low frequencies, where the phase angles are small, the energy losses are small. When frequencies are high, the strain cannot response fast enough to the applied stress, so energy loss remain small too. Thus, the energy loss is highest between the two frequency limits, when the phase angle and the strain amplitude assume relatively large values. When temperature increases, the mobility of molecules increases, and the strain can track the dynamic stress more closely. With lower temperatures, stiffening of the material occurs. Therefore, the same effect can be achieved by either of the following :

1. Increase of temperature or decrease of frequency.
2. Decrease of temperature or increase of frequency.

This correspondence allows one to experimentally determine the behavior of materials at frequencies higher than typical apparatus may accommodate by decreasing the sample temperature. Likewise, an experiment can obtain very low frequency performance predictions by measuring the response of sample at elevated temperatures.

Factors like molecular weight, composition of the elastomer, pressure, *etc*, have their effects on the dynamic properties of the viscoelastic materials but they are not included in this study. [Ref. 14]

As the dynamic response of a viscoelastic material depends on the temperature and frequency [Ref. 10 : Chap.11] , it appears to be most convenient if one of the two variables is being held constant while the other varies. Nevertheless, only a small range of viscoelastic behavior can be observed over the experimentally accessible frequency range, therefore a complete characterization of the material and its viscoelastic transition is only possible through measurements over a limited range of frequencies at various temperatures. This is the most popular approach to characterize viscoelastic materials in the field today, and it is based on the method of reduced variables developed by Williams, Landel and Ferry [Ref. 10 : pp. 294 - 320]. The treatment yields a master curve relating a chosen dynamic property such as storage modulus to a reduced frequency through a temperature-frequency shift factor, a_T . Each material has its own expression for this temperature-frequency factor. The development of this temperature-frequency factor is discussed in depth in the original paper of Williams, Landel and Ferry [Ref. 15].

In the resonant bar technique, it is required that measurement be made at discrete frequencies which correspond to the normal-modes of the bar. When the temperature of the bar varies, the resonant frequency changes also, and it is tracked by a phase-locked-loop (PLL) which will be discussed in Chapter III. The two variables of interest, *i.e.*, temperature and frequency, are coupled and this presents a challenging problem in presenting and analyzing the experimental data. This problem is rather unique. In the more established technique using an accelerometer as a receiver and a shaker table as a driver [Ref. 16], the excitation frequency can be chosen independently of the temperature. Therefore, it can be seen that the resonant bar technique presents a simple solution to the problem of characterization of material under dynamic stress but with variables that are coupled together. In contrast, the direct measurement method using accelerometer is able to isolate the variables but it is mathematically more complex due to the large mass loading induced by the accelerometer and the attachment to the shaker table. To verify the application of this technique in the investigation, an effort was made to select a material that has been investigated by authorities in this research area, in particular, by Capps of the Naval Research Laboratory - Underwater Sound Reference Detachment (NRL-USRD). The experimental data obtained in this investigation are converted to reduced frequency using the empirical formulae given in Capps' report [Ref. 16].

III. EXPERIMENTAL APPARATUS

A. INTRODUCTION

The resonant bar theory is based on simple wave equations. Experimentally, it is also easy to set up, very repeatable due to the free-free boundary condition, and easy to operate. Moreover, with the electrodynamics transduction scheme, one can selectively excite torsional, flexural, or longitudinal modes using the same sample, transducer pair, and experimental set up and thus it is extremely versatile. There is no other known apparatus that can excite all three modes with the same set up, same transducers and with virtually no mass loading effects. Basically, the set up consists of the following components :

1. Test sample.
2. Two transducers mounted on the sample.
3. Test jig for supporting the sample and providing the magnetic field for the transducer coils.
4. Electronic instrumentation and computer/controller.

B. SAMPLE

1. Preparation of Materials

With the exception of PMMA, the samples used in the study each consisted of two potting components, the resin (part A) and the hardener (part B). They are mixed together in proportions recommended by the manufacturers. The epoxies E-CAST® F82/215, PR1592 and EN9, were heated and degassed at 50°C before mixing. Epoxies PR1570 and EN5, were mixed and degassed at room temperature. The epoxies are heated and degassed in an oven equipped with a vacuum pump. The data sheets for the epoxies are included in Appendix B.

2. The Casting of Sample

The cylindrical rod shaped samples are typically 30 cm in length and 1.27 cm (0.5") in diameter, so that a large *L/d* ratio is achieved. The apparatus can accommodate samples of dimensions with diameters of 1.2 ± 0.5 cm and lengths of 30 ± 10 cm. The samples are made by pouring the prepared elastomers into a mold. The molding tubes for these samples are thick walled (1/8") Teflon® tubing with inner diameter of 0.5 ± 0.05". Teflon® is used as the mold material due to its release properties. It does not require any mold release agent in the preparation of a sample.

3. Curing

After the polymer is poured into the mold, the epoxy is cured according to manufacturer's recommendation. When the epoxy is properly cured, the sample is pushed out from the Teflon® tubing. A post cure (at 50°C for 24 hours) is carried out so that the properties of the sample reach their final stable state. Figure 3 shows the sample cast from epoxy EN9 with attached transducer coils and thermistor.

C. TRANSDUCER COILS

The transducers that act as the driver and receiver of the resonant bar are identical in construction. Each consists of No. 32 gauge copper wire with a nominal diameter of 0.2 mm which are approximately one meter in length, and wound into a 10-turn coil. Each coil weighs about 0.56 gram. They are glued to the ends of the sample by a general purpose plastic cement (GC Electronics 10-324). The ends of the coil are stripped of their insulating layer, and are then coated with solder to assure good conductivity. After each coil is prepared, a continuity check is done to ensure that it is capable of driving and receiving of signals. The coil typically has a resistance of about 1.1 Ω. If a large signal is desired, the turn ratio can be increased by a factor of N, thus increasing the the signal by N^2 at the expense of added mass of coil. If this added mass becomes significant, a simple effective length correction factor can be included in the analysis of the result [Ref. 3]. The elastic properties of the plastic cement are not expected to affect the observed resonance and in-phase magnitude of the bar.

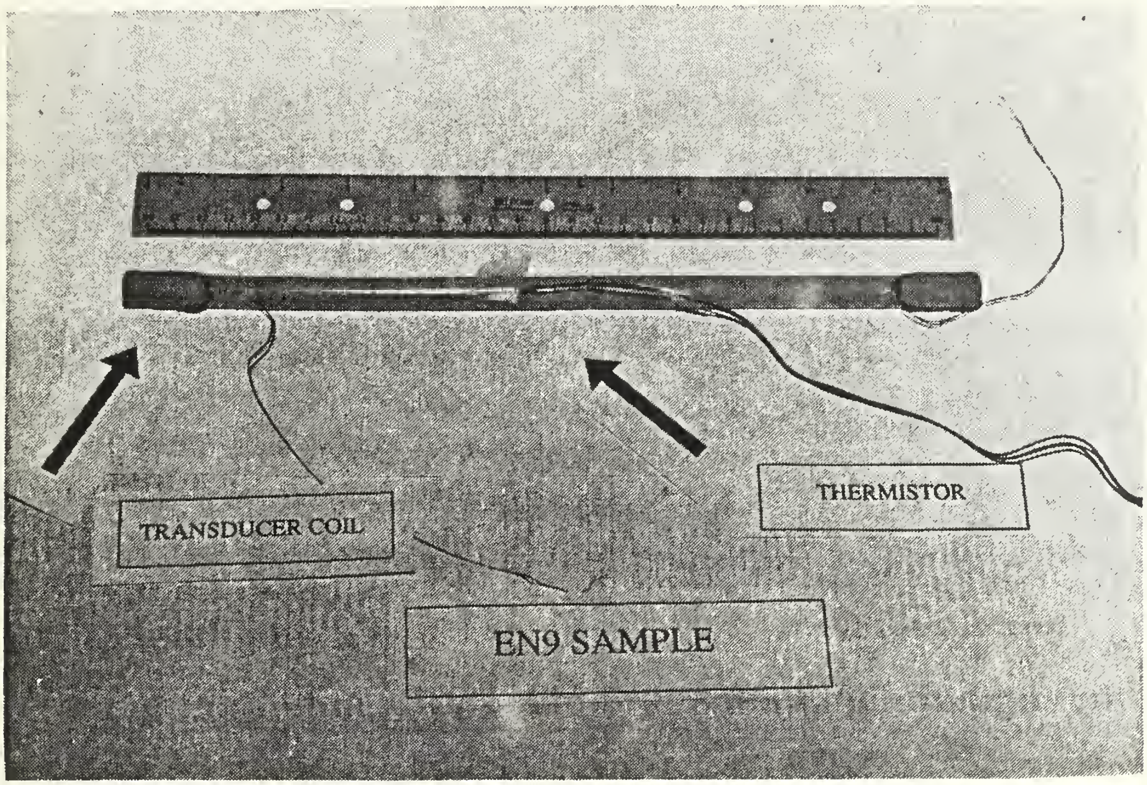


Figure 3. Photograph of a prepared EN9 material sample.

D. APPARATUS

The apparatus used in this research, shown in Figure 4, was constructed "in-house" based on a commercial apparatus [Ref 4]. The apparatus is made up of an excitation system, an adjustment system and a suspension system. The electrodynamic excitation system has two pairs of permanent magnets. They provide the necessary magnetic field, so that a varying sinusoidal electrical signal can be converted into a mechanical driving force or torque and the reciprocal effect. The gap between the magnetic poles is approximately two centimeters and it is adjustable to accommodate samples of different diameters. The magnetic field strength in the gap is approximately 2.4 ± 0.1 KOe (0.24 Tesla) over a temperature range of -17°C to 85°C. The temperature dependence of the magnets was determined to be -2.3 Oe/°C. One pair of the magnets is attached to a sliding platform to accommodate samples of different lengths.

The suspension system for the material sample consists of a pair of "X" supports with rubber bands in a crisscross manner. The rod-shape sample is then placed on the two supports so that a free-free boundary condition can be realized. The "X" supports can be raised or lowered vertically and they can slide horizontally. This is useful as they can support the material sample at any desired points and heights. The smallest effect from the suspension supports is achieved when the rod is placed so that the vibrational nodes rest on the "X" supports. This is not necessary for high loss materials due to the fact that the suspension losses are relatively low as has been quantified in this research (see Chapter IV Section C).

E. ENVIRONMENTAL CHAMBER

An environmental chamber is used to control the temperature of the material sample under test. The model used is BHD-408 Bench-Top Temperature and Humidity Test Chamber manufactured by Associated Environmental System. It has a internal dimensions of 24" (Height) x 24" (Width) x 24" (Depth). The temperature range of the system is -17°C to 85°C and the temperature control stability is ±0.5°F (approx. ±0.3°C). It has a dual loop controller capable of independent operation, or it can be controlled by a host computer through a IEEE 488 Interface. For the controller, a computer like the HP9000 series computer can be used. For our application, the local control mode is used. The detailed specification of the chamber is provided in Appendix C .

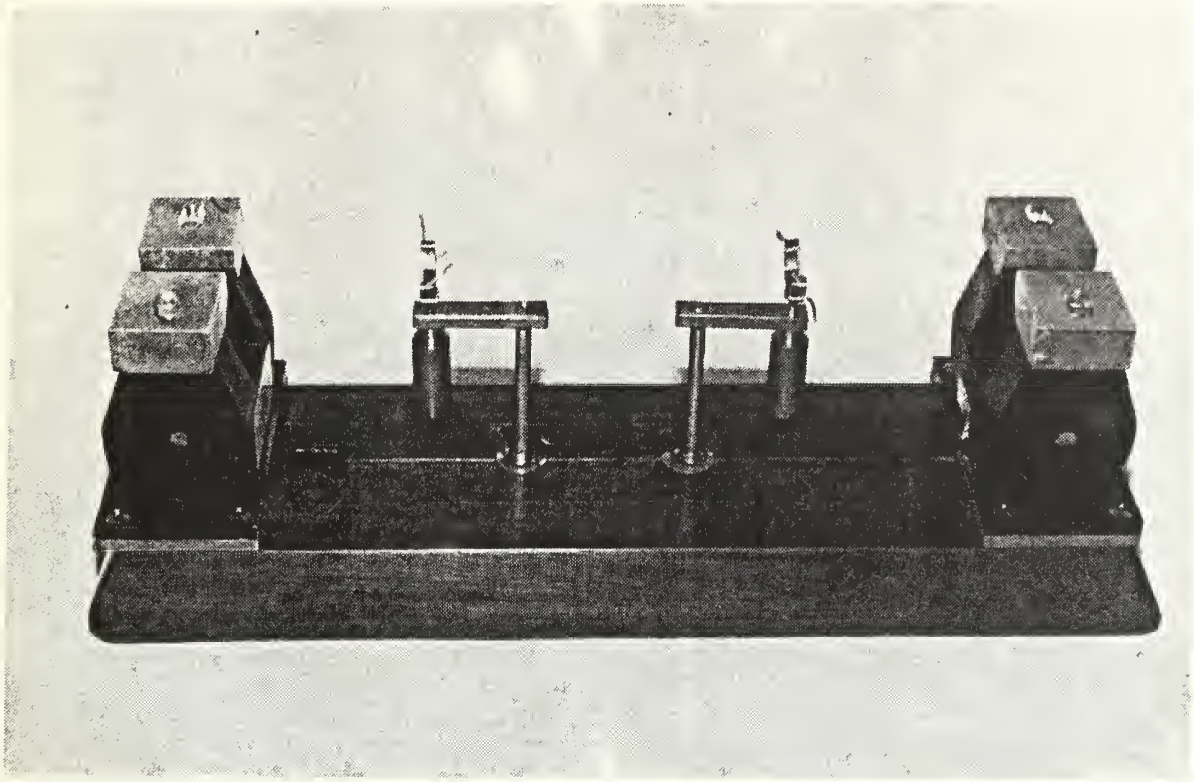
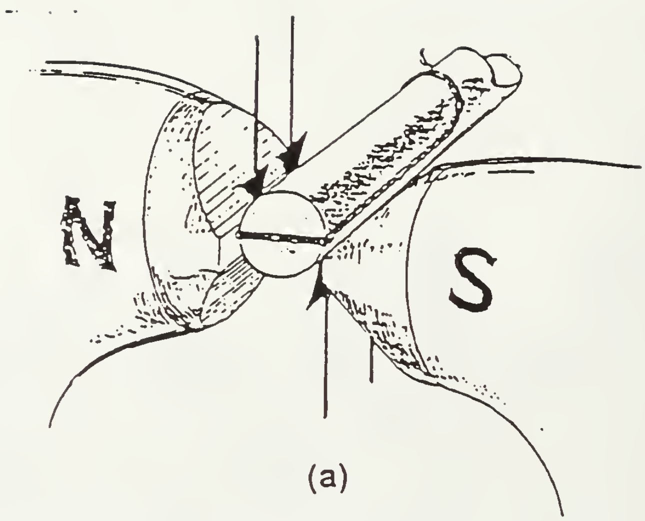


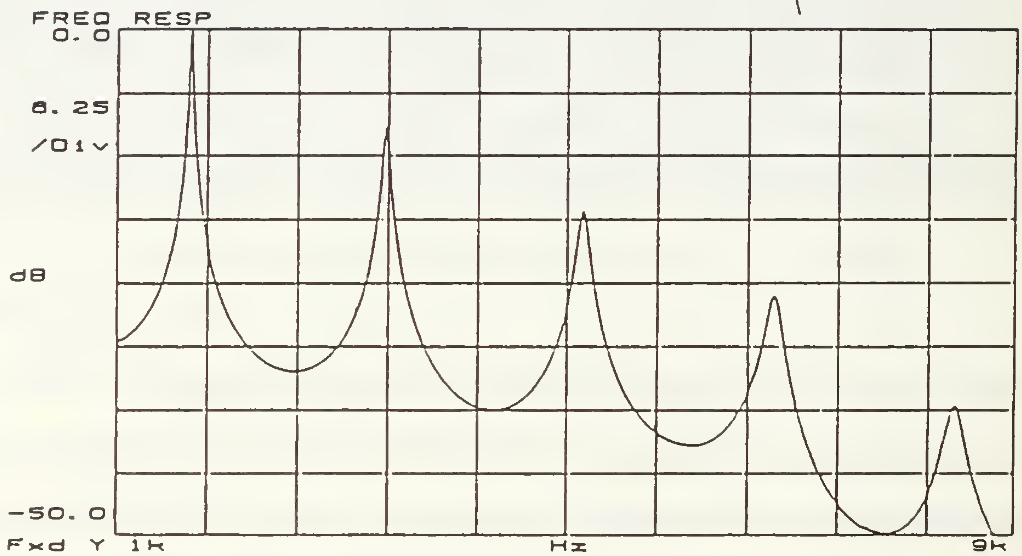
Figure 4. Resonance based moduli measurement apparatus.

F. SELECTION AND EXCITATION OF A DESIRED MODE

The material sample is positioned on the apparatus so that the ends of the sample and the transducer coils are in the vicinity of the maximum magnetic field strength during the dynamic moduli measurements. The mode of excitation can be selected by the orientation of the coils within the magnetic field. Figures 5, 6, and 7 shows the relative arrangement of the coil and magnetic field to produce the torsional, flexural and longitudinal vibration respectively. A detailed discussion can be found in Garrett's paper [Ref. 3].



(a)



(b)

Figure 5. Torsional vibration excitation and detection scheme
(a). Arrangement for torsional vibration, the arrows indicate the direction of the electromagnetic forces on the coil for a given phase of current.
(b). The torsional frequency response of F-28

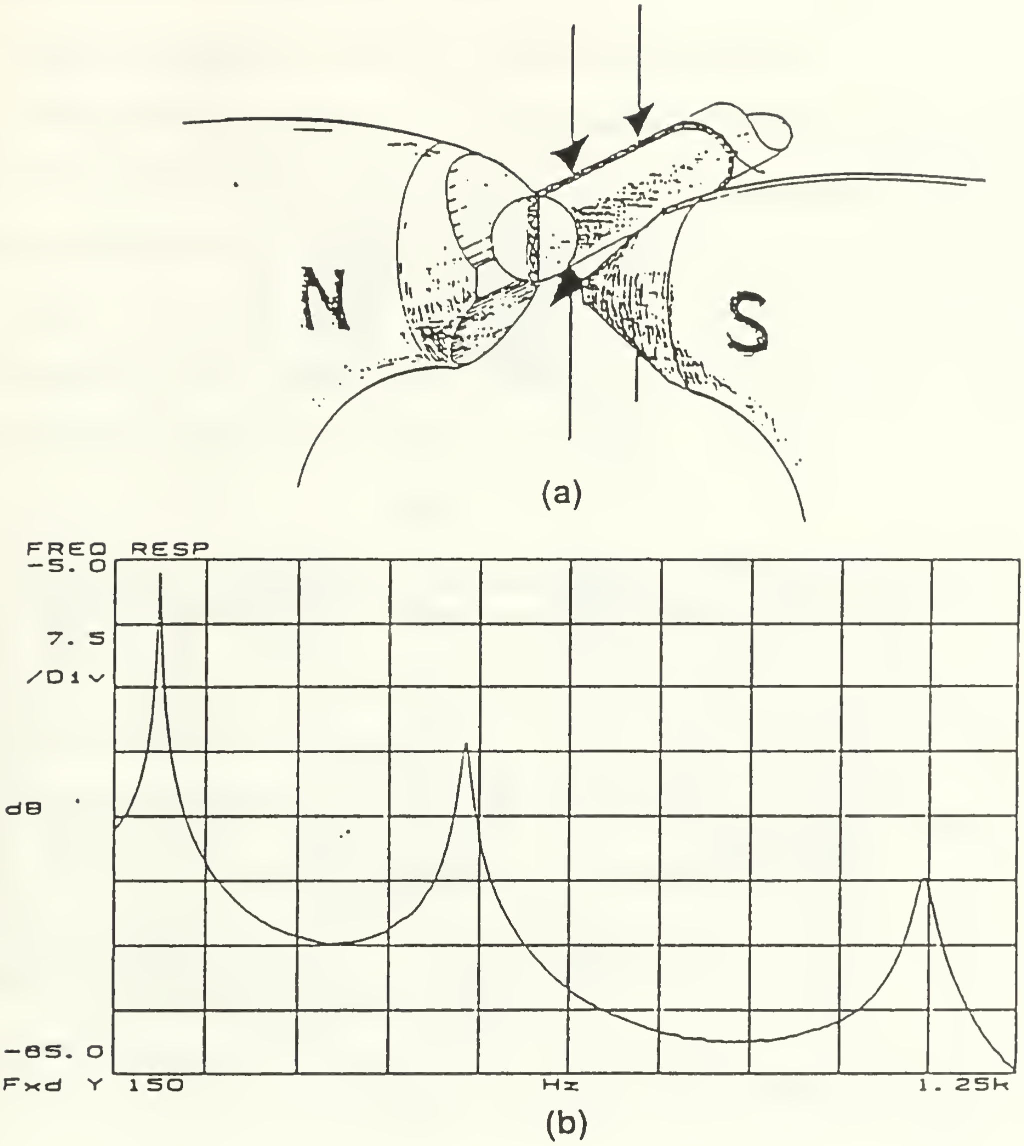
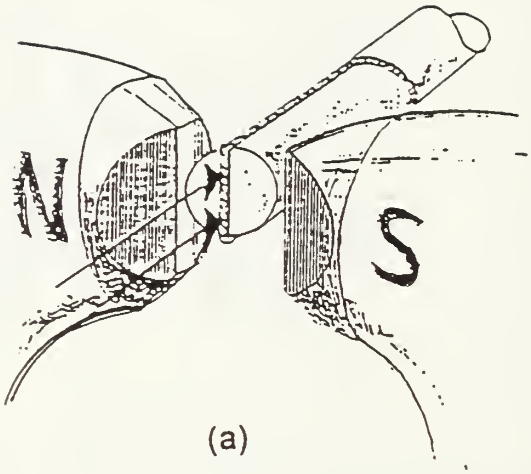
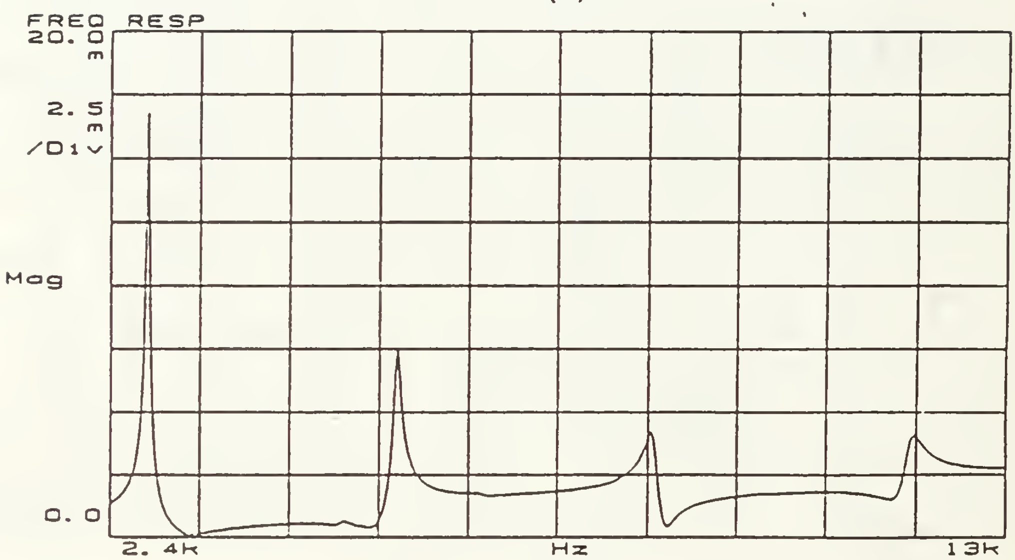


Figure 6. Flexural vibration excitation and detection scheme
(a). Arrangement for flexural vibration, the arrows indicate the direction of the electromagnetic forces on the coils for a given phase of current.
(b). The flexural frequency response of F-28.



(a)



(b)

Figure 7. Longitudinal vibration excitation and detection scheme

(a) Arrangement for longitudinal vibration, the arrows indicate the direction of the electromagnetic forces on the coils for a given phase of current.

(b) The longitudinal frequency response of F-28.

G. ELECTRONIC INSTRUMENTATION

1. Room Temperature Dynamic Moduli Determination

The instrumentation required for determination of dynamic moduli at room temperature is shown in Figure 8. The HP3562A Dynamic Signal Analyzer is used as a signal source as well as a receiver, so that the frequency response of the material sample can be obtained. The excitation signal used is a swept-sine wave with a driving output from the amplifier (HP467A) of typically two to three volts peak-to-peak. Typical frequency response are shown in Figure 5(b), 6(b), and 7(b).

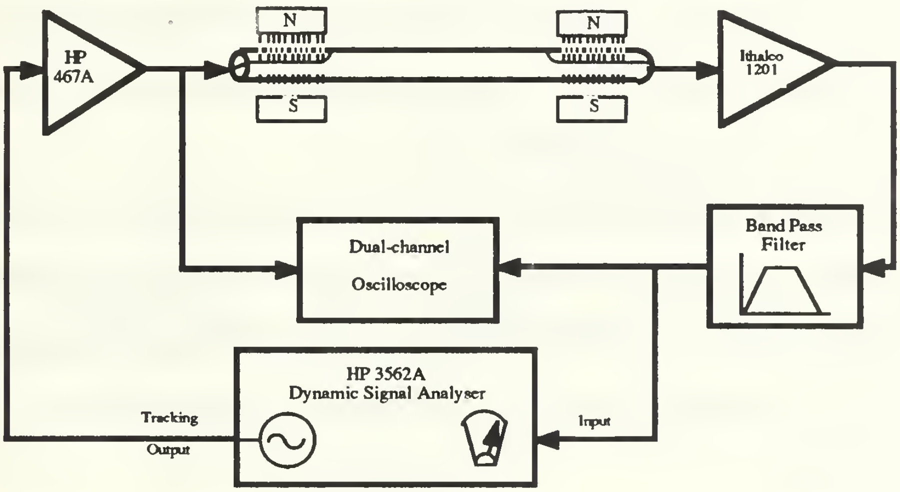


Figure 8. Block diagram of the instrumentation used at room temperature.

The HP3562A has a built-in curve fit function which is used in the study extensively. Using this pole-zero plot curve fit function, the quality factor, resonant frequency, and loss factor can be calculated. The theoretical basis for obtaining the resonance frequency and quality factor from the pole-zero plot is discussed in Brown, Tan and Garrett's paper in Appendix A.

2. Temperature and Frequency Dependence of the Dynamic Moduli

The instrumentation for this measurement is shown in Figure 9. The temperature of the material sample is varied by an environmental chamber. Using a lock-in amplifier and a voltage controlled oscillator (VCO) in a phase-locked-loop configuration, the resonant frequency of a selected mode of the material sample is tracked. When the temperature of the specimen changes, its resonance frequency changes due to the changes in the modulus. There is also a contribution to the change in frequency due to the change in the length of the sample via the coefficient of thermal expansion, but this effect is small by comparison and is neglected in this study. Using a HP9836C computer as a system-controller through the HPIB, readings of the temperatures, resonant frequencies of the sample and the in-phase component of the lock-in amplifier can be recorded. A listing of the control program is included in Appendix D.

The sample rod is placed on the apparatus in the same manner as in the dynamic moduli determination at room temperature. The temperature of the rod is monitored by a thermistor (HP0837-0164) which is compatible to the HP3456A Digital Voltmeter. The voltmeter is set up to read the thermistor temperature in degrees Celsius (°C) with a resolution of 0.001°C.

The procedure of this measurement is to identify the modes of the bar at room temperature first, as discussed previously, and then select a given mode for automatic tracking with temperature. This is done by tuning the voltage controlled oscillator (VCO) manually to resonance with the integrator shorted and the error signal feedback path open so that there is no error signal presented to the voltage control (feedback) point. The phase shifter is then adjusted so that there is zero output from the quadrature signal channel of the lock-in amplifier. The integrator can then be opened and the control loop completed. If the resonance "runs away", the signal (either transmitter or receiver) needs to be inverted. This

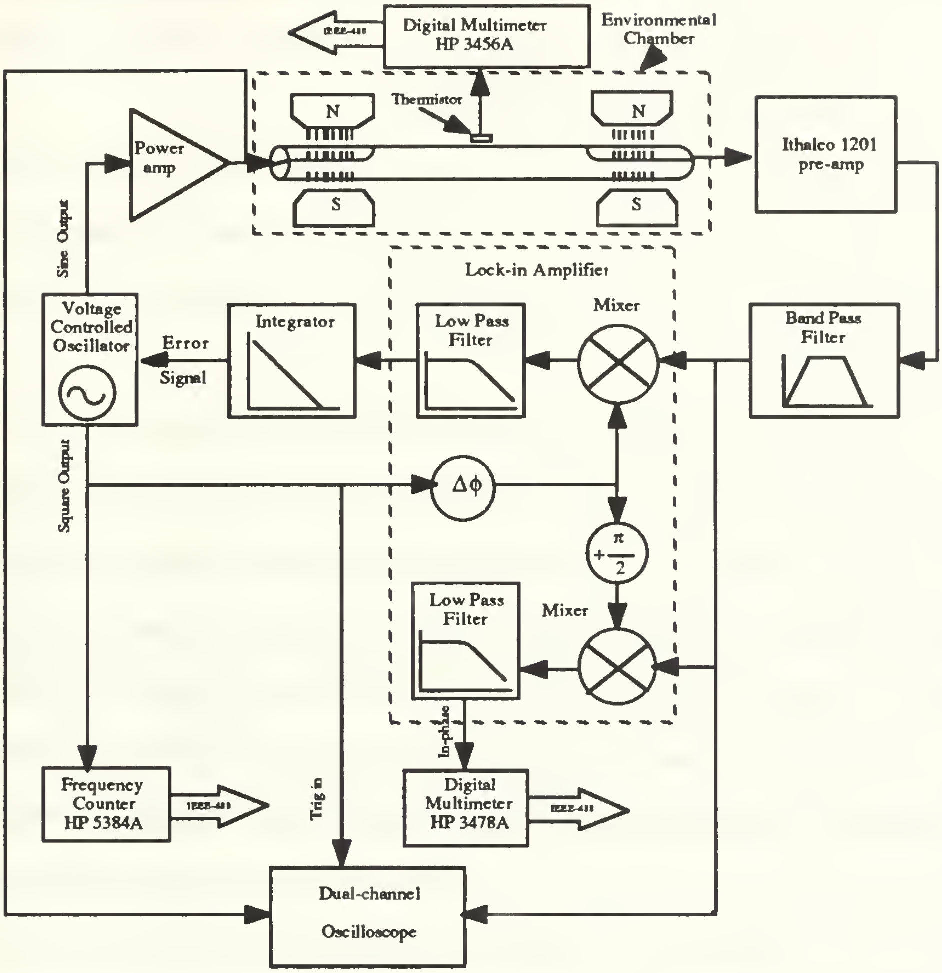


Figure 9. Block diagram of the instrumentation used to track the dynamic moduli dependence on temperature and frequency.

is most easily accomplished by shifting the phase an additional ± 180° if a lock-in analyser is being used as the mixer/phase shifter/low pass filter. It may also be necessary to adjust the filter time constant and amplifier gain if the signal oscillates. Once the control loop is locked and stable, the temperature may varied.[Ref.3]

After setting up the PLL, the environmental chamber is programmed to run a temperature profile as shown in Figure 10. The long time interval is used to achieve a quasi-equilibrium state, so the material sample is in equilibrium with the uniform temperature environment.

The nature of the experimental set up calls for automation. Thus, in their material selection study [Ref. 6], Beaton has written a BASIC program using the HP9000 series 200 computer Model 236C to acquire inputs of temperature and frequency data. The program is modified to include the input from the in-phase component of the lock-in amplifier and to extend the duration of the measurement from 40 minutes to 20 hours.

To facilitate the graphical presentation of data, the data are converted from the HP data format to Macintosh Cricket Graph™ format. Using a software package called MacTerm for Macintosh II and software written by Professor Steven R. Baker of NPS (Appendix E) for HP9000 series computer, the data recorded in HP BDAT file are transported from the HP9000 computer via a RS 232C port to the Macintosh II computer.

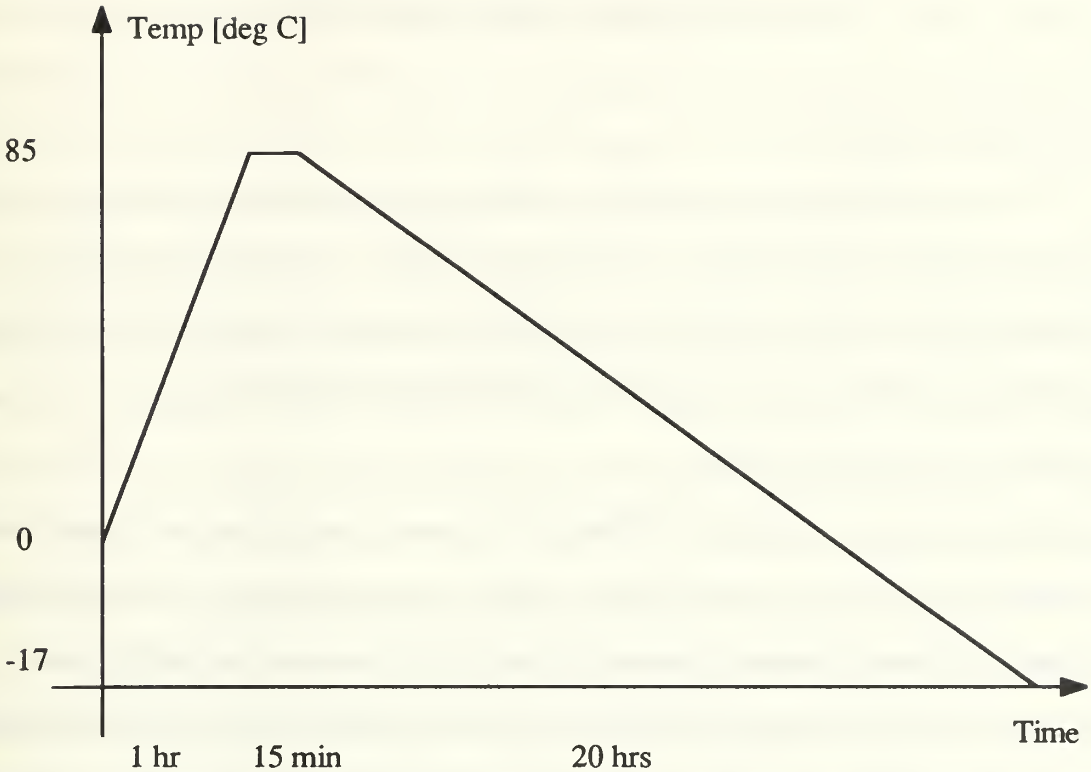


Figure 10. Typical temperature profile for the dynamic moduli measurement

IV. SYSTEM VERIFICATION

A. INTRODUCTION

To investigate the complex moduli of a material using the resonant bar technique, it is essential to quantify the losses due to the suspension system. As mentioned earlier, the computations of the moduli are based on a free-free boundary condition. This assumption is valid when the suspension has a negligible effect on the response of the rod.

B. INITIAL INVESTIGATION

An existing sample rod of E-CAST® F82/215 that was used in a previous experiment involving fiber-optics (see Appendix A) was initially chosen to investigate the losses due to the suspension system. The quality factor, Q, which is a measure of the energy stored to the energy lost per acoustic cycle (Chapter II, equation (23)) was measured, for various support positions (Figure 11) and two types of suspensions: rubber bands and fishing line. As the suspension positions one and three illustrated in Figure 11 correspond to the nodal position of mode two and three respectively, it is expected that the losses are lower than the non-nodal placement positions.

The experimental set up is shown in Figure 8, Chapter III. The HP3562A Dynamic Signal Analyzer is used to generate a swept sine signal which is used as the reference input (channel 1) for the HP3562A. This signal is amplified by HP467A power amplifier and then applied to the driver coil. The electrical signal is converted to a mechanical driving force through the magnetic field and the transducer coil electrodynamic interaction. The response of the material sample is then converted to an electrical signal through the reciprocal electrodynamic transduction mechanism. The received signal is amplified and filtered by an Ithaco 1201 pre-amplifier and input to the second channel of HP3562A.

Plotting the ratio of these two inputs as a function of frequency, the frequency response of the sample material can be obtained directly using the HP3562A. Typical frequency response curve is shown in Figure 5(b). Using the built-in curve fit function of the HP3562A, the quality factor and resonant frequency of each resonant mode can be determined from the pole-zero table generated by HP3562A (see Appendix A).

From Table 1(a), it can be seen that quality factor of mode one and mode two is almost identical, but mode three and mode four differ from these two modes by approximately 5% and 10% respectively. Using the grand average as the reference, only mode four deviates by about 10%. It is noted that, suspension position three produces the highest quality factor in the third mode as expected, but suspension position one produces the lowest quality factor in the second mode instead of the highest which is not the expected result.

From Table 1(b), response of mode three and four is equal within 5%. The quality factor of mode one is the lowest and for mode two it is the highest. Except for mode one, the other modes are less than 18% different from the grand average. Suspension position three has the highest quality factor within the third mode as expected and it is significantly higher than the average quality factor within the mode. Suspension position one does not produce the highest quality factor in second mode as it is expected, although it is the second highest among the quality factors obtained in the same mode.

The experiment was repeated and the similar observations were made. Thus, within the experimental uncertainty, we may conclude that the suspension loss contribution is small and it will be substantial only if a very high quality factor material is under investigation.

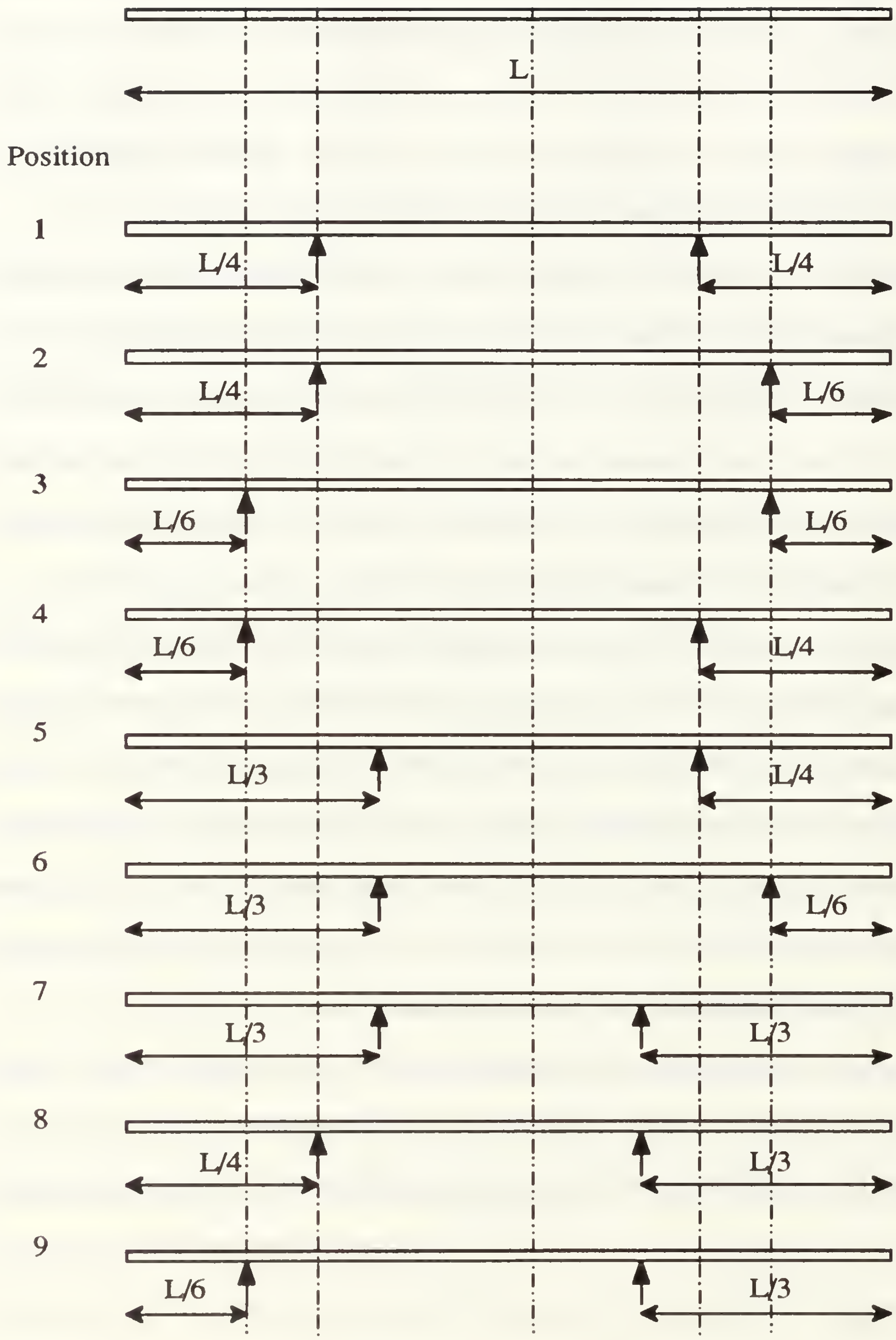


Figure 11. Support positions used in suspension loss measurements
−·− and −··− indicate the nodal positions of second and third mode respectively

TABLE 1. QUALITY FACTOR OF E-CAST® F82/215 OBTAINED FROM DIFFERENT SUSPENSION POSITIONS IN TORSIONAL VIBRATION

(a) RUBBER BAND SUSPENSION

Position	1st Mode	2nd Mode	3rd Mode	4th Mode
1	22.20	21.79	21.01	19.83
2	22.83	22.29	21.48	19.92
3	23.09	22.51	21.76	19.71
4	22.12	23.02	21.41	19.42
5	22.89	22.47	21.20	20.37
6	22.01	22.19	21.24	20.67
7	21.94	22.32	21.18	20.45
8	22.49	22.40	21.17	20.44
9	22.68	22.28	21.27	20.48
Average	22.4 ± 0.4	22.4 ± 0.3	21.3 ± 0.2	20.1 ± 0.4

Grand average: 22 ± 1

TABLE 1. QUALITY FACTOR OF E-CAST® F82/215 OBTAINED FROM DIFFERENT SUSPENSION POSITIONS IN TORSIONAL VIBRATION

(b) FISHING LINE SUSPENSION

Position	1st Mode	2nd Mode	3rd Mode	4th Mode
1	15.47	**22.97**	20.89	19.20
2	12.57	22.84	20.77	19.21
3	10.55	22.73	**21.59**	19.45
4	10.31	23.12	21.46	18.88
5	14.71	22.38	20.43	19.31
6	12.95	22.30	20.12	20.10
7	17.78	21.51	19.77	20.10
8	14.72	21.92	19.09	19.79
9	12.05	22.04	20.60	19.61
Average	13 ± 2	22.4 ± 0.5	20.5 ± 0.8	19.5 ± 0.4

Grand average: 19 ± 4

C. SUSPENSION LOSS DETERMINATION USING AN ALUMINIUM SAMPLE

The total losses of a forced vibration system in the resonant bar technique is the sum of the intrinsic losses due to the sample's material properties, suspension losses due to the suspension system of the apparatus and radiation losses. Radiation loss is considered to be negligible and therefore, to be able to measure the intrinsic loss of a sample material, an upper bound must be placed on the suspension losses.

For a high Q material, the resonant peak is very sharp and its -3 dB bandwidth is very small. If the Q of the material is of the order of 1000, then the required sweep time, oscillator stability, and sample temperature stability become a problem both with instrumentation and the patience of the experimentalist. Therefore, we can not simply replace the E-CAST® F82/215 by the 6061T6 aluminium rod and repeat the swept sine frequency response measurements using the HP3562A and expect to obtain accurate curve fit parameters (poles and zeroes) for the quality factor.

The half-power point measurement of Q also depends on the frequency resolution and is not suitable due to the temperature stability of the resonance frequency. Another approach that "exploits" the high Q characteristics of the system was used. As the reciprocal of frequency is time, one can use a time measurement technique that has a long time record, and thus an equivalent high frequency resolution to measure the Q of a low loss material. Free decay measurements is one of such techniques that involves the measurement of successive attenuated amplitudes, from which the damping and hence the quality factor can be obtained. Since a long time record means large amount of data can be generated, regressional analysis can be performed to minimize any random errors due to decaying amplitude variation in the determination of the exponential decay time, τ.

A block diagram of instrumentation for the free decay measurement is shown in Figure 12. The sample is driven at one of the resonant frequencies and the tone burst excitation is abruptly removed. This is achieved by means of the trigger pulse switch which disconnects the driving signal to the transducer coil and at the same time provides a trigger pulse to the external trigger input of the Nicolet digital storage scope which records the response of the material sample. Using a digital storage scope and linear regression analysis, the quality factor of the sample can be determined. A typical graph of the measurement is shown in Figure 13. The results are summarized in Table 2 where the uncertainties in Q result from the uncertainty of the slope as determined by the least square method. Based on the average of multiple measurements, the systematic error is larger than the random error when the quality factors are this large and the losses are correspondingly small. From these results, it can be seen that the difference of the quality factors between the "best" and "worst" support positions varies from 24% to 43% for the first three modes.

It can therefore be concluded that for a low loss (high Q) system, the suspension loss makes a significant contribution to the total losses of the suspension system/sample combination as currently configured. Using the worst case analysis, the suspension loss is about 43% for a system with a Q of about 1300. For a high loss (low Q) system, such as the F82/215 sample, that has a Q of about 20 (and most viscoelastic materials with Q's typically less than ten, see Chapter V, Table 5), the suspension loss contributes less than 1% to the total losses of the entire system.

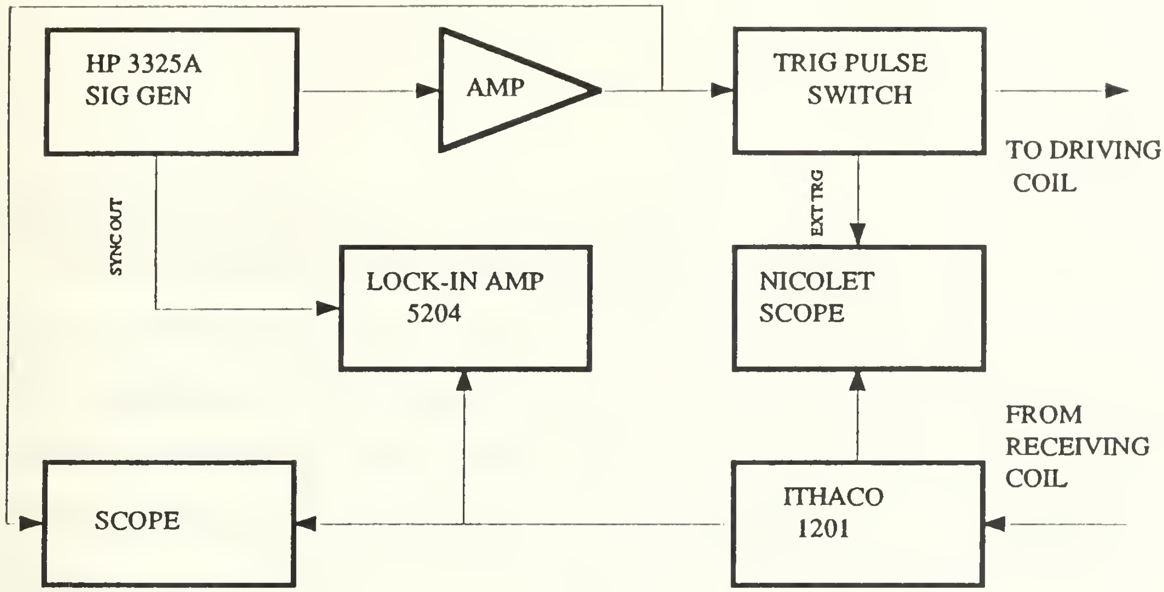


Figure 12. Block diagram of the free decay measurement of aluminium rod

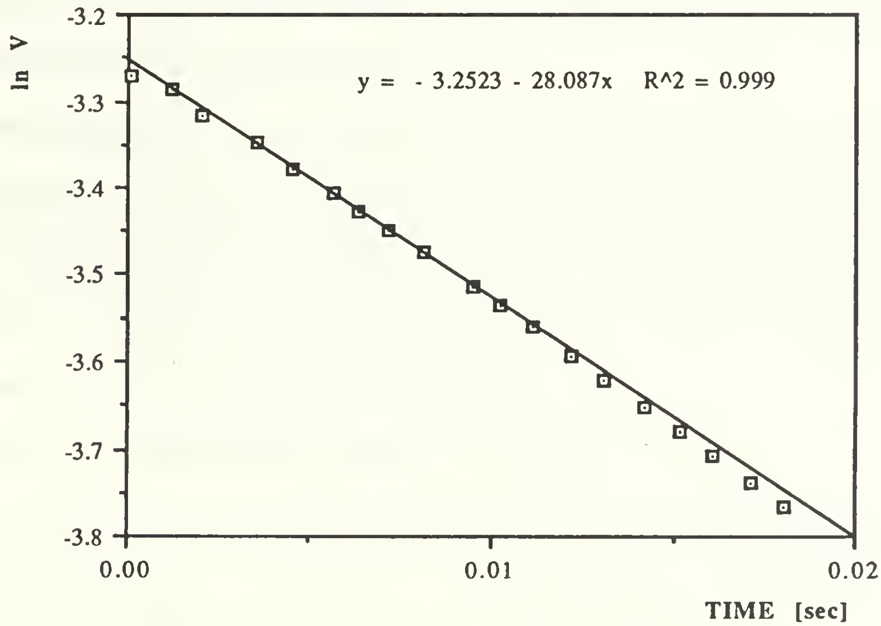


Figure 13. Free decay measurement of *Q*

TABLE 2. QUALITY FACTOR OF 6061T6 ALUMINIUM ROD OBTAINED FROM TWO DIFFERENT SUSPENSION POSITIONS USING FREE DECAY METHOD .

	1st Mode	2nd Mode	3rd Mode
Best support	1306 ± 0.8% 1338 ± 0.4%	868.7 ± 0.6% 830.5 ± 0.9%	1222 ± 1.4% 1437 ± 0.8% 1792 ± 1.3%
Average ± σ	1320 ± 16	850 ± 20	1500 ± 300
Worst Support	751 ± 0.4%	644.9 ± 0.4% 653.5 ± 0.5%	968 ± 5% 940 ± 3% 934 ± 4%
Average ± σ	751	650 ± 5	950 ± 18
Relative difference	43 %	24 %	36 %

V. DATA

A. INTRODUCTION

This study consists of three main areas. The first is the verification of the resonant bar technique to determine the elastic properties of a sample material called E-CAST® F82/215. The second portion involved quantifying the suspension losses using E-CAST® F82/215 and 6061T6 aluminium bar sample. The results of the suspension losses were reported in Chapter IV. The third section is the investigation into the temperature and frequency dependence of the elastomeric materials: Uralite 3130, PR1592 and plexiglass or polymethyl methacrylate (PMMA). Uralite was chosen because of its use in fiber-optic hydrophones [Ref.17], PR1592 because of an accessible NRL-USRD report [Ref.16], and PMMA because of its wide use as a "standard" material in viscoelastic investigation.

B. PRELIMINARY INVESTIGATIONS

To gain experience with the resonant bar technique, some preliminary measurements were made on E-CAST® F82/215 to determine its dynamic moduli at room temperature. The result, which is summarized in Table 3, where ρ is the mass density, G is the shear modulus, and E is the Young's modulus, agreed with those obtained in Reference 6 which used a similarly constructed resonant bar apparatus.

TABLE 3. DYNAMIC MODULI OF E-CAST® F82/215

	ρ [kg/m^3]	G [GPa]	E [GPa]	σ
Ref. 5	1120	0.91±0.06	2.5±0.2	0.37
Present study	1120±20	0.96±0.06	2.70±0.05	0.40

A fiber optic interferometer was constructed by embeding a fiber which comprised of one of the legs of a Michelson interferometer, into a E-CAST® F82/215 rod. In this study, the interferometric output is used as second means to determine the resonant frequency of the rod. It is being investigated for smart skin applications to monitor the state of strain of struts. The results were reported in the proceedings of the SPIE Conference "Fiber Optic Smart Structures and Skins III" in San Jose, September 1990. That paper is included as Appendix A.

C. TEMPERATURE AND FREQUENCY DEPENDENCE OF VISCOELASTIC MATERIALS

1. Test Matrix

In this study, Uralite 3130, PR1592 rods cast in Teflon® tubing and PMMA rods were used. The torsional mode is the easiest mode to excite and detect, and thus most of the data collected were on the shear modulus. For the PR1592, data was also collected for the flexural resonant mode which depends on the Young's modulus. The test matrix is as follows

TABLE 4. TEST MATRIX FOR VISCOELASTICITY MEASUREMENTS

	PR1592	PMMA	U3130
Torsional	✓	✓	✓
Flexural	✓	—	—
Quality Factor	✓	✓	—

2. Data Presentation for PR1592, PMMA and U3130

The resonant bar technique produced data with the two variables, frequency and temperature, coupled together. That is, neither was held constant through a measurement run. This was discussed in Chapter II. The temperature-frequency dependence measurement of the first four torsional modes of PR1592 have been investigated in this study. Graphs produced from the data are shown in Figure 14 and Figure 15. Note that the points were taken at arbitrary time intervals, in this case, every five minutes. The resonance is tracked continuously, thus the discrete data points which are presented could have been obtained with different data density. It can be seen from Figure 14 that as frequency increases, the shear modulus increases in a quadratic manner. As the higher order mode is examined, the slope of the response curve reduces at each frequency. In Figure 15, the higher modes have a higher value of shear modulus at a constant temperature. Further, it can be observed that at the highest temperature, the shear modulus of all the four modes approaches a constant value asymptotically as expected in a single relaxation time constant system discussed in Chapter II. The temperatures were not large enough to obtain the high temperature asymptotic behavior.

The experimental data was then plotted in three dimensional space to visualize the relationships between shear modulus, temperature, and frequency. To compute the loss tangent, the quality factor, Q , of specimen was measured as a function of temperature. In order to present the data in the conventional format, Capps' [Ref. 16 : p. 210] and Ferry's [Ref. 10 : p.316] results were used to determine the temperature-frequency shift factor a_T necessary to obtain the master curve.

a. Three Dimensional Plots

The effects of temperature and frequency on the behavior of a viscoelastic material can be most easily visualized in a three dimensional plot. The following sections will discuss the various data obtained to construct the three dimensional plots.

(1) Shear Modulus. The three dimensional plots are shown in Figure 16, Figure 17 and Figure 18 for PR1592, PMMA and Uralite 3130 respectively. In Figure 16, all the data from the lowest four torsional modes of PR1592 are presented.

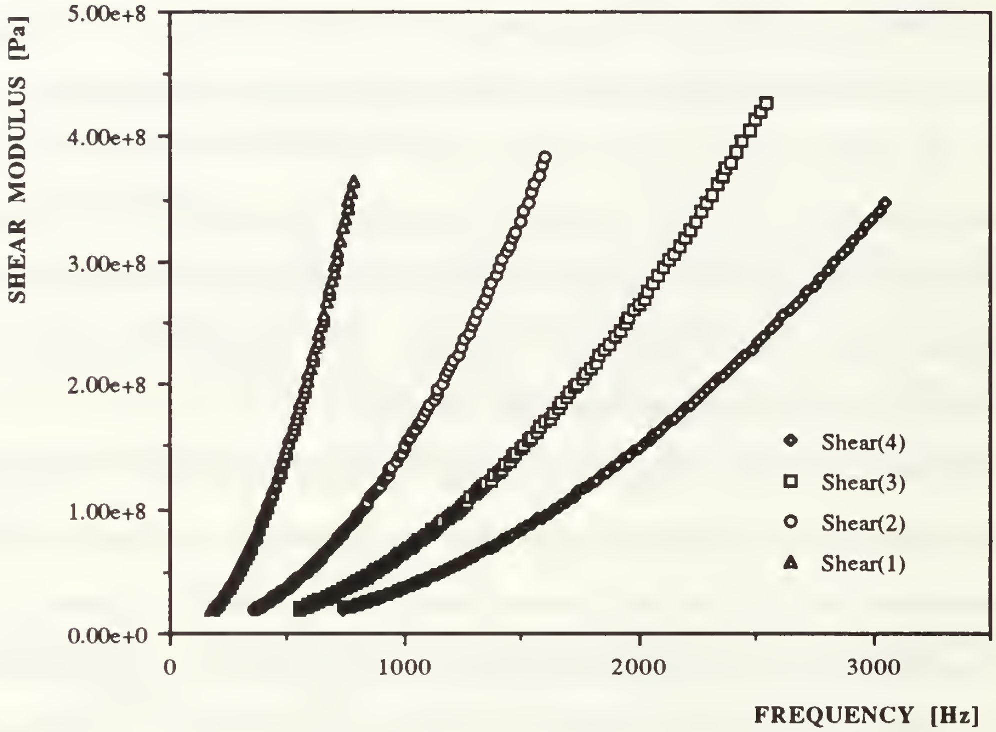


Figure 14. Shear modulus of PR1592 plotted against resonance frequency (temperature is not constant). The numeric indicates the mode number.

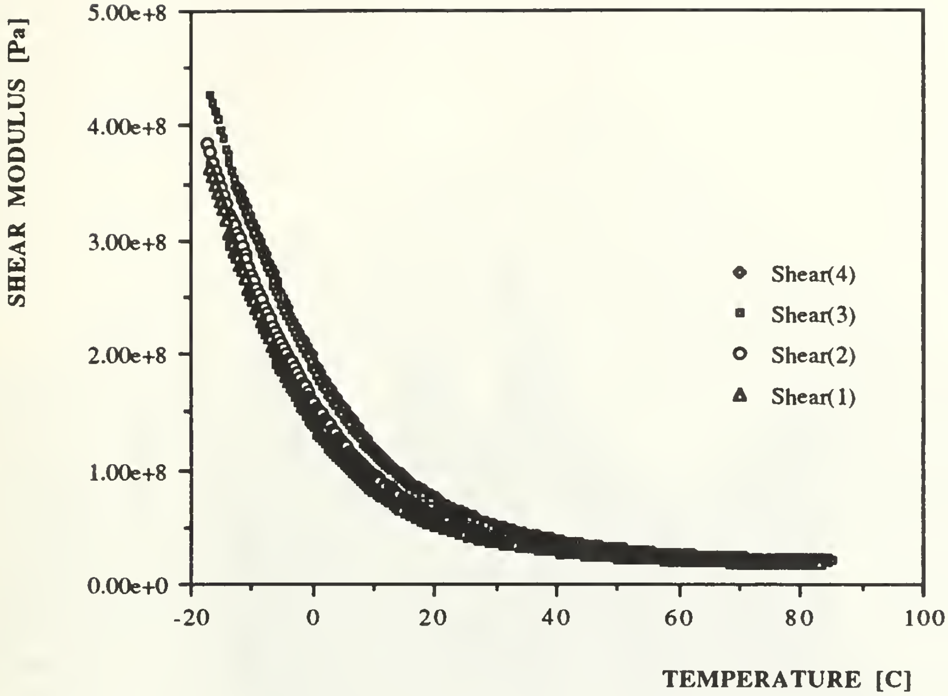


Figure 15. Shear modulus of PR1592 plotted against temperature.

It can be seen that all these are smooth, continuous curves. As temperature increases, the resonant frequency decreases and the shear modulus decreases correspondingly. Both Uralite 3130 and PR1592 are "rubbery" materials at room temperature. The curvature of the projection of their three dimensional modulus graphs in the frequency-temperature plane is opposite to that of the PMMA which is in the "glassy" state at the temperature of this study. When the higher resonant mode is used, the resonant frequency increases and the span of frequency also increases, however, the amplitude of the in-phase output of the lock-in amplifier decreases. Lastly, it can be seen that, the shear modulus is not a simple function of temperature and frequency.

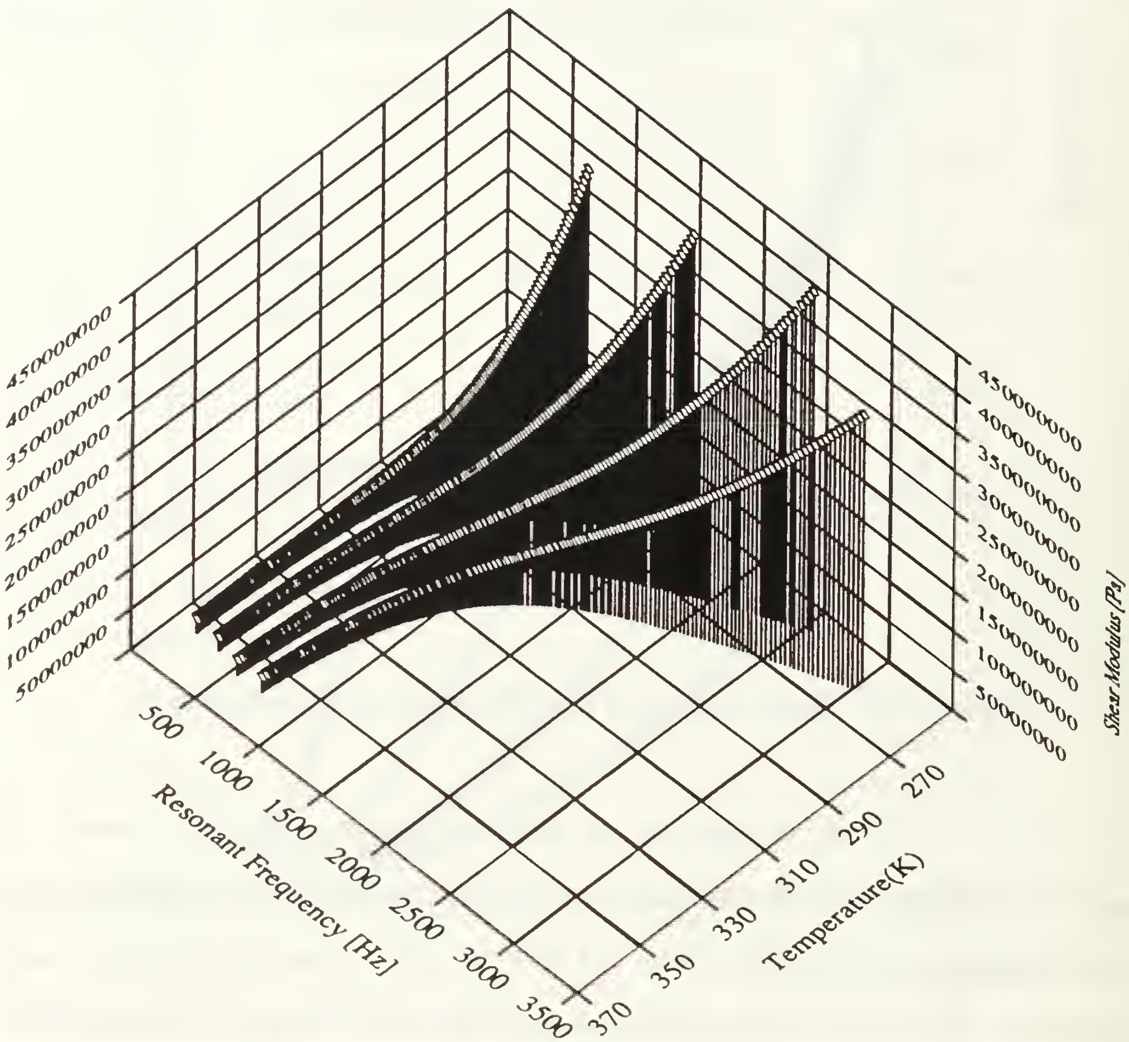


Figure 16. Shear modulus of PR1592 as a function of frequency and temperature.

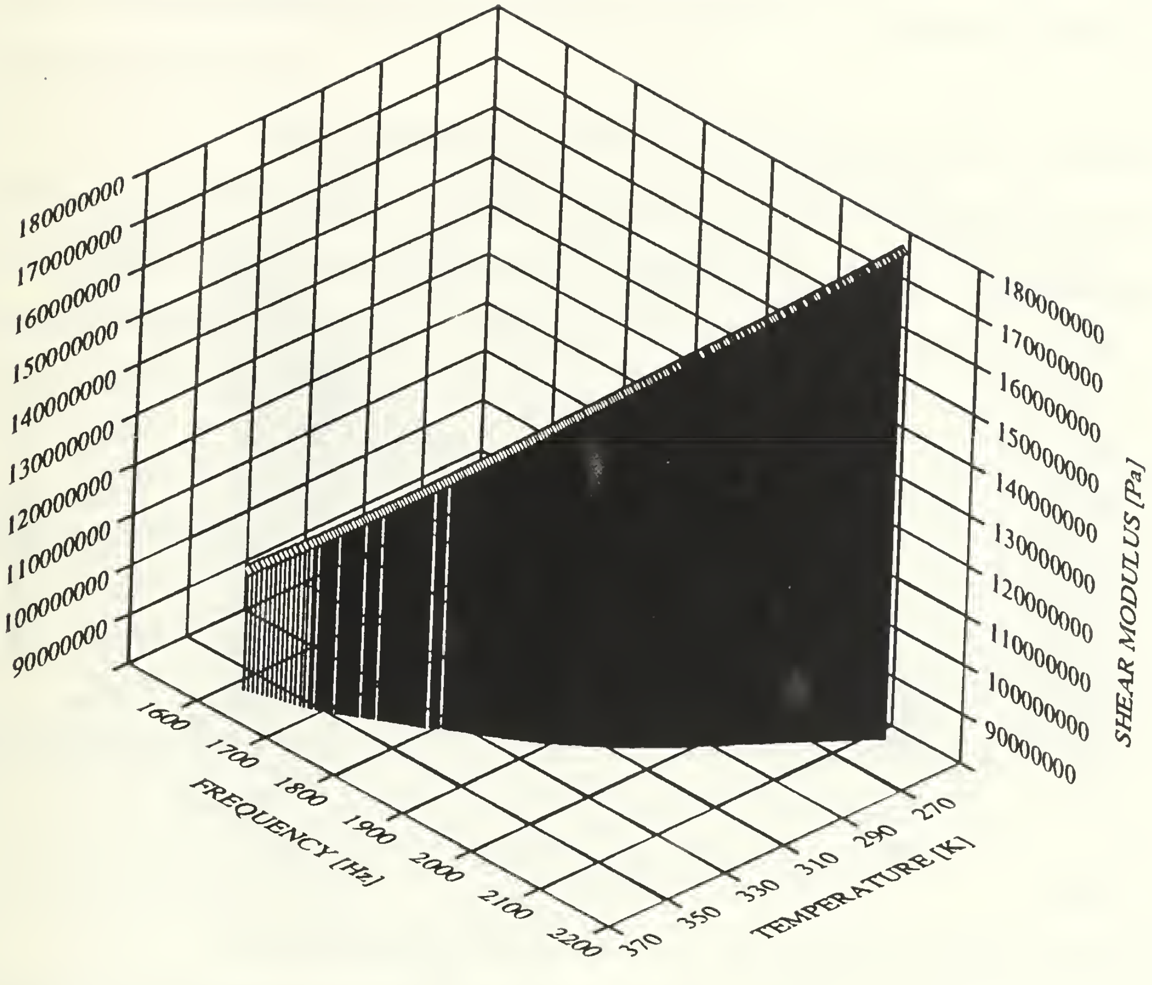


Figure 17. Shear modulus of PMMA as a function of frequency and temperature.

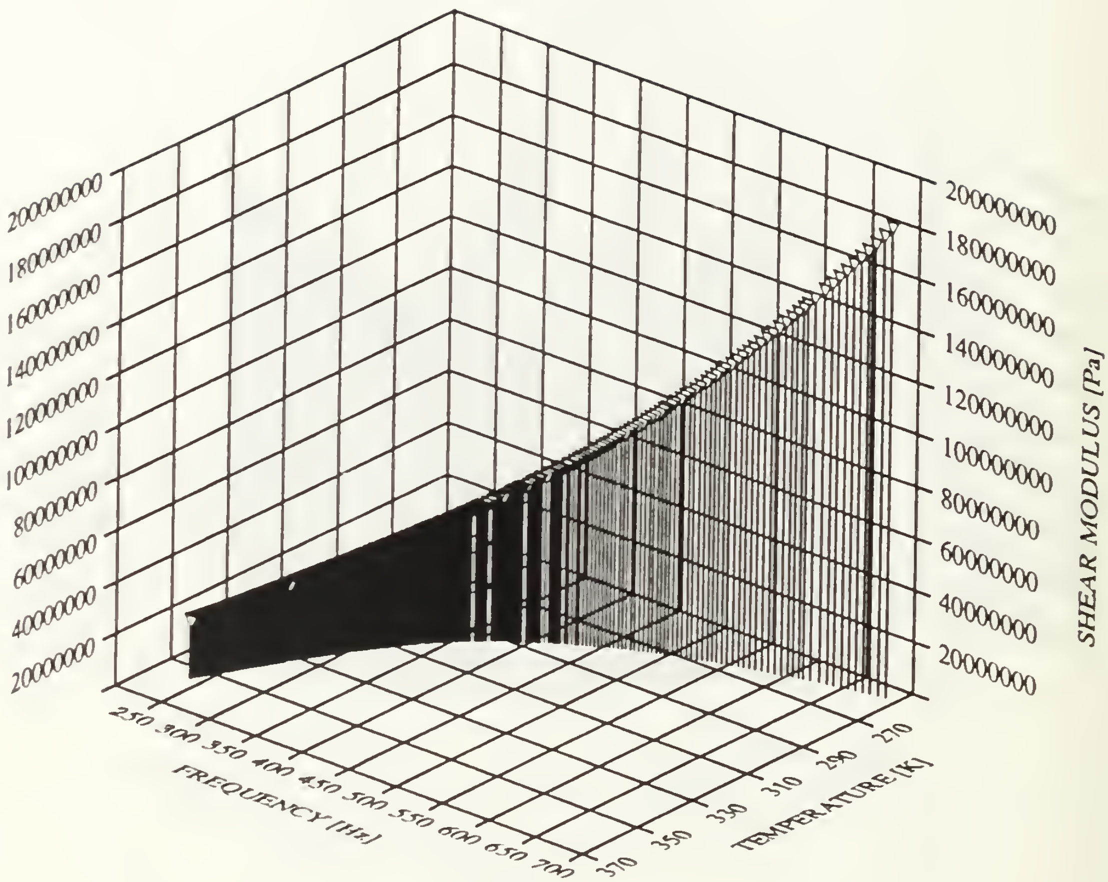


Figure 18. Shear modulus of U3130 as a function of frequency and temperature.

(2) Loss Tangent. The three dimensional plots of the loss tangent of PR1592 and PMMA are shown in Figure 19 and Figure 20 respectively. For PR1592, the presence of glass-rubber transition is evident. The graph of loss tangent has a maximum. There is no local maximum in the loss tangent plot of PMMA for the range of frequencies and temperatures tested.

From Chapter II equation (28), it is shown that the ratio of quality factor, Q , to product of vibrational speed of the end of the bar and resonance frequency, fu, is a constant. Since the in-phase output, V_{in} , of the lock-in amplifier is proportional to this speed, equation (28) can be rewritten as

$$\frac{Q}{V_{in}f} = b \quad , \tag{30}$$

where b is a constant of proportionality. Noting that,

$$tan\ \delta = \frac{1}{Q} \, , \tag{31}$$

and combining equations (30) and (31), the loss tangent can be expressed as

$$tan\ \delta = \frac{1}{bV_{in}f} \, . \tag{32}$$

By measuring the quality factor, Q, and in-phase voltage at a set of temperatures and frequencies, the loss tangent empirical constant b can be obtained at the start of a test and then the loss tangent of the sample material can be determined continuously. One set of results used to obtain a value for the constant b is shown in Table 5. For this example, the constant has a value of 64 milliseconds per volt (msec/volt). The standard deviation of the 13 measurements is 8 msec/volt so the uncertainty is 2.3 msec/volt or about ±4%. The reader should be cautioned that this constant is a function of the position of the coils and the gain of the pre-amplifier and lock-in amplifier. Thus, it must be determined for each sample and instrument setting used.

(3) Young's Modulus. The plot of Young's modulus of PR1592 is shown in Figure 21. It was obtained using the flexural mode of the sample material.

b. *Master Curves*

The conventional way to present viscoelastic behavior is to use the master curve. The master curves are produced from reduced frequency for the shear modulus or loss tangent. The reduced frequency is calculated from data of Capps [Ref. 16 : p. 210] and Ferry [Ref. 10 : p.316].

The general form of the temperature-frequency shift factor, a_T, based on the WLF equation [Ref. 10 : chap.11], for a great variety of polymers can be expressed as

$$\log a_T = \frac{-8.86\,(T - T_s)}{101.6 + T - T_s}, \tag{33}$$

where T is the absolute temperature in degrees Kelvin K, and T_s, is the reference temperature in K. The equation is applicable at temperature about 50° C above the glass transition temperature. However, as discussed in Ferry [Ref. 10 : chap.11] , it is better to determine specific values of the two constants in this equation for each sample. Therefore, to explore this particular area, constants from the measurements of Capps for PR1592 and Ferry for PMMA were used. Their expressions are as follows

$$\log a_T = \frac{-12.9\,(T - 283.15)}{107 + T - 283.15}, \tag{34}$$

for PR1592 and

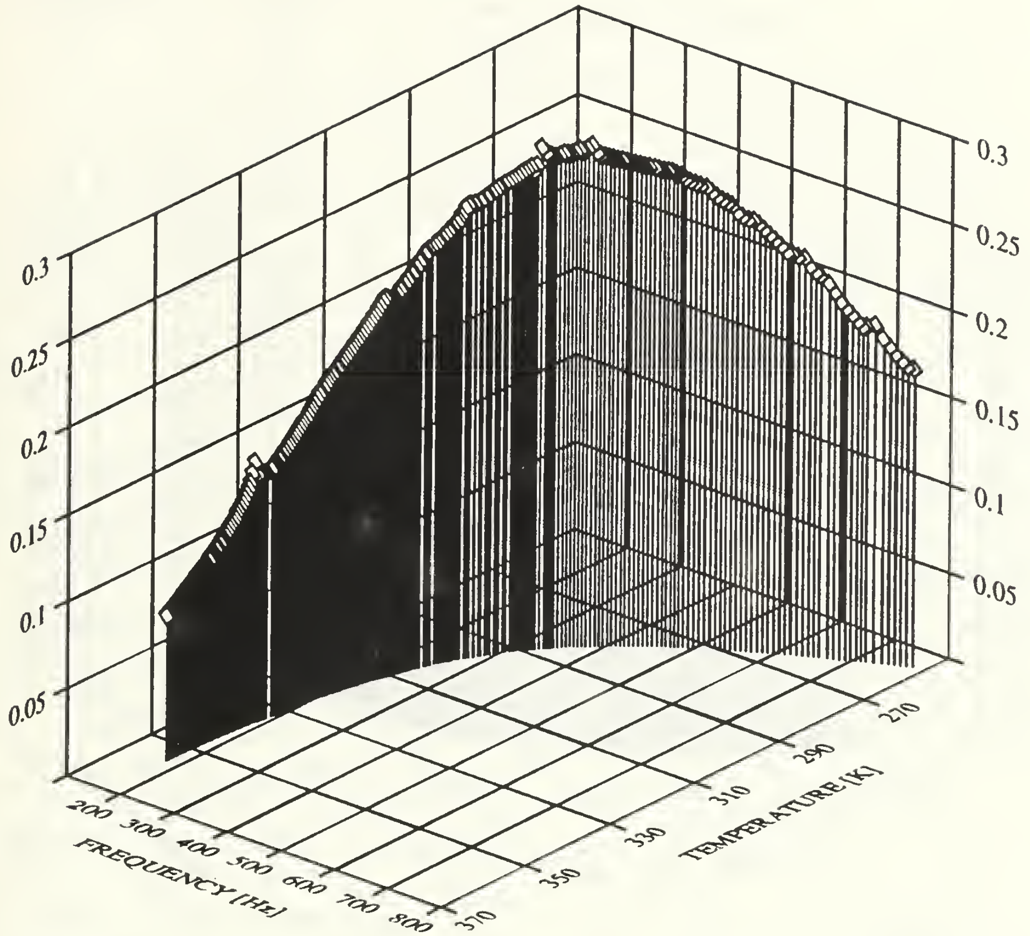


Figure 19. Loss tangent of PR1592 as a function of frequency and temperature.

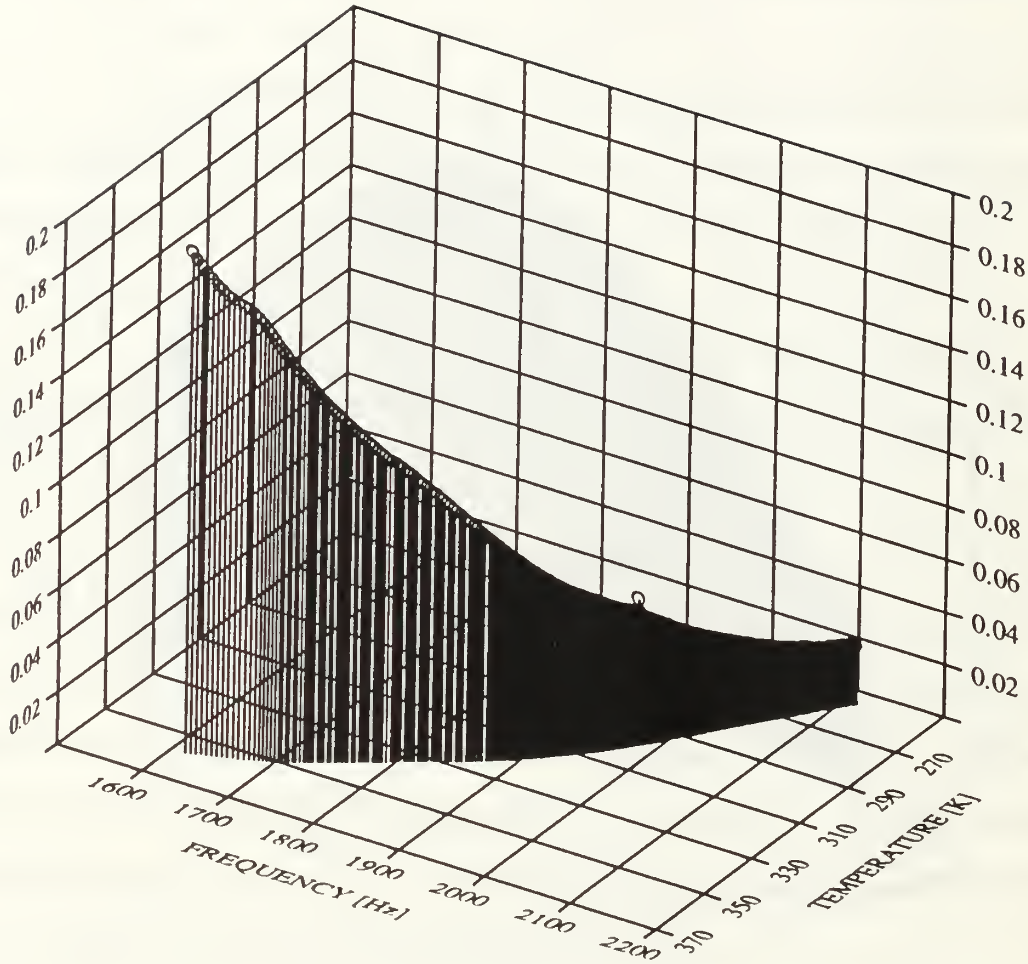


Figure 20. Loss tangent of PMMA as a function of frequency and temperature.

TABLE 5. DETERMINATION OF THE LOSS TANGENT EMPIRICAL CONSTANT " *b* ".

T Temperature [C]	f Frequency [Hz]	V_{in} In-phase voltage [DCV]	Q Quality factor	Q/fV_{in} [msec/V]
-17.138	801.9	-0.1125	5.523	-61.22
-10.124	678.4	-0.1048	3.825	-53.80
-0.224	515.2	-0.1140	4.378	-74.53
0.085	511.5	-0.1147	2.913	-49.65
9.321	398.7	-0.1372	2.927	-53.51
19.430	306.5	-0.1842	3.415	-60.49
29.480	259.4	-0.2452	3.847	-60.48
39.342	231.6	-0.3142	5.082	-69.84
49.096	217.1	-0.4092	6.304	-70.97
58.929	201.7	-0.5401	7.805	-71.66
69.546	195.0	-0.7048	9.701	-70.58
79.561	190.0	-0.9350	12.41	-69.86
84.277	188.1	-1.0700	13.60	-67.58

Average: -64 ± 8 msec/V

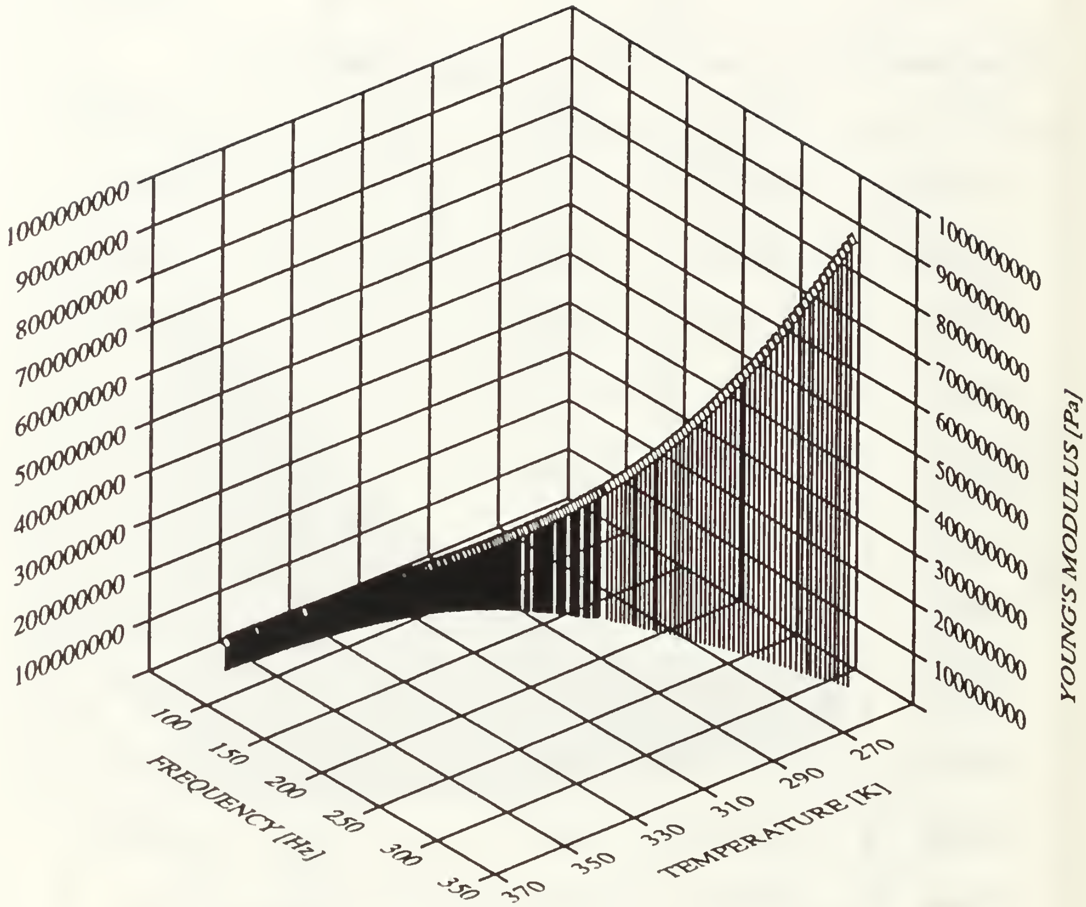


Figure 21. Young's modulus of PR1592 as a function of frequency and temperature.

$$\log a_T = \frac{-21.5\,(T - 211)}{43.1 + T - 211}, \qquad (35)$$

for PMMA. The parameter, a_T, was not independently determined in our study since we did not have sufficient time to use samples of different length. Samples with different lengths would allow moduli at the same temperature but with different frequencies, which were sufficiently well separated to determine the temperature-frequency shift factor with adequate precision.

(1) Shear Modulus and Loss Tangent. The plots of the master curve for the shear modulus of PR1592 and PMMA are shown in Figure 22 and Figure 23 respectively. It should be noted that, for a one order-of-magnitude change of frequency and a temperature range of 100° C (approximately 30% change in absolute temperature), there is a ten-order-of magnitude change of the corresponding reduced frequency. This is rather extraordinary, and it demonstrates the strong dependence of the dynamic modulus of viscoelastic materials on temperature.

From Figure 22, it can be clearly seen that there is a transition from rubbery plateau to glassy zone for PR1592. This is evident from the maximum in the loss tangent curve which is a characteristic of a glass-rubber transition region. By inspection, for PR1592, the transition has occured at a reduced frequency of about 100 Hz, assuming a reference temperature of 10°C.

However, looking at the data obtained from the PMMA (plexiglass) sample, only the glassy zone and part of the glass-rubber transition region are observed. This is also evident in the loss tangent curve in which the loss tangent increases monotonically as the reduced frequency decreases.

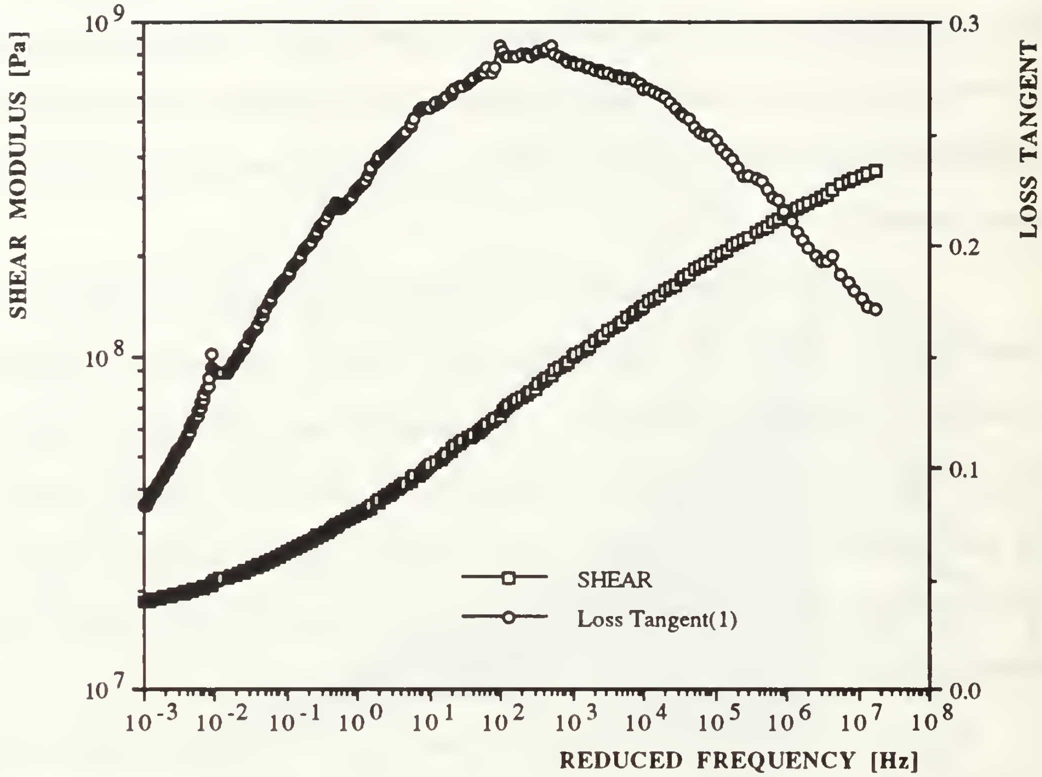


Figure 22. Master curve of PR1592 based on the measurement of the first torsional mode.

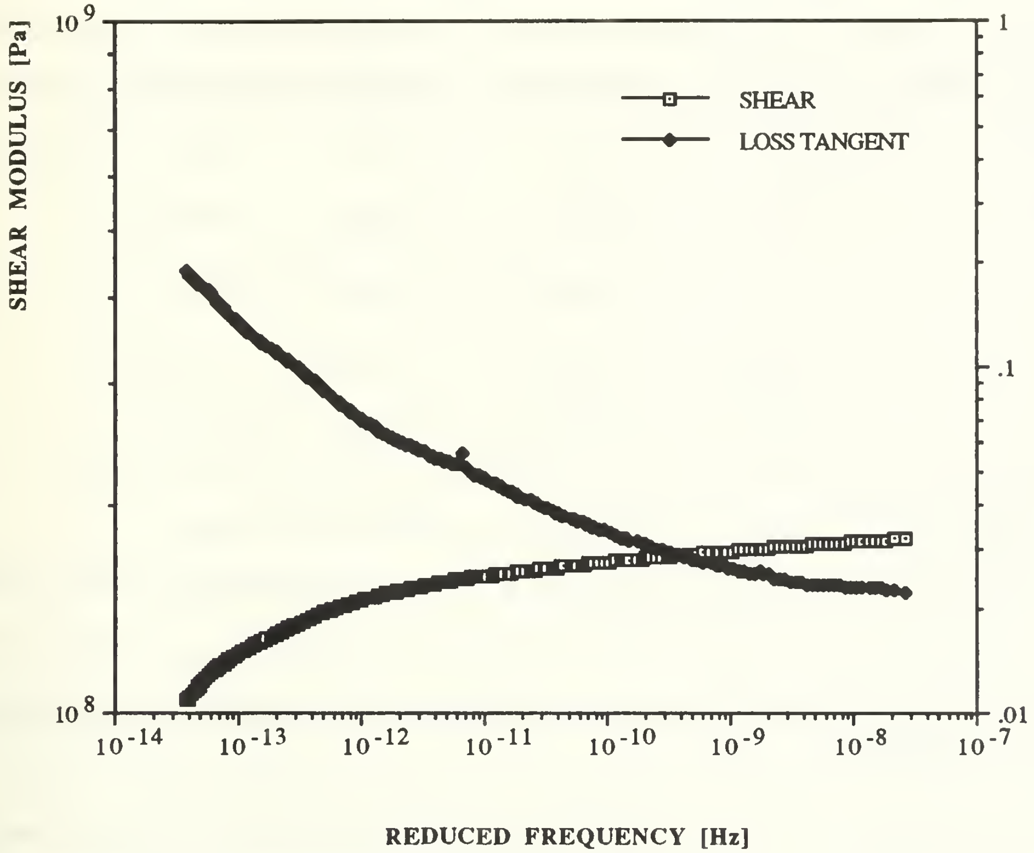


Figure 23. Master curve of PMMA based on the measurement of the first torsional mode.

TABLE 6. COEFFICIENTS OF CURVE FIT FOR PR1592 TORSIONAL MODE

Coefficient	1st mode	2nd mode	3rd mode	4th mode
a0	7.5324	7.5210	7.5607	7.5529
a1	0.13067	0.13592	0.13998	0.13972
a2	1.0742e-2	1.1154e-2	1.1289e-2	1.1633e-2
a3	-1.162e-3	-1.159e-3	-1.949e-3	-1.757e-3
a4	-1.679e-5	2.309e-5	5.790e-5	1.876e-5
Correlation Coefficient	1.000	1.000	1.000	1.000

TABLE 7. COEFFICIENTS OF CURVE FIT FOR LOSS TANGENT (TORSIONAL MODE)

	PR1592		PMMA
Coefficient	1st Mode	2nd Mode	1st Mode
a0	-0.63667	-0.60388	9.0104
a1	7.2174e-2	7.8122e-2	4.2034
a2	-1.8544e-2	-2.1478e-2	0.61220
a3	1.6625e-3	1.3403e-3	3.9509e-2
a4	-1.1907e-4	-4.5023e-5	9.8409e-4
Correlation Coefficient	0.998	0.998	0.999

The master curves for PR1592 are fitted to a fourth order polynomial function given in equations (36) and (37) and the coefficients for the shear modulus is tabulated in Table 6. The coefficients of the loss tangent of PR1592 and PMMA are given in Table 7.

$$Log\ G = \sum_n a_n(Log\, f)^n \ , n = 1,2,3,4. \tag{36}$$

$$Log\ (tan\ \delta) = \sum_n a_n(Log\, f)^n \ , n = 1,2,3,4. \tag{37}$$

By inspection of Figure 22, we see that the location of the inflection point in shear modulus occurs at approximately the maximum of the loss tangent as would be expected for a simple relaxation model discussed in Chapter II. Differentiation of the fourth order polynomial fits to the shear modulus and loss tangent yields an inflection point at $log\ a_T f = 2.85$ for shear modulus and a maximum at $log\ a_T f = 2.65$ for loss tangent. This is considered to be in excellent agreement for the span of $log\ a_T f$ which is from -3 to 7, over ten order-of-magnitude.

(2) Young's Modulus. As for the shear modulus, the master curve for Young's modulus uses the same fourth order polynomial curve fit. The result is shown in Table 8.

TABLE 8. COEFFICIENTS OF CURVE FIT FOR PR1592 FLEXURAL MODE - YOUNG'S MODULUS

Coefficient	1st mode	Capps' result
a0	8.0219	7.71248
a1	0.12331	0.12531
a2	9.985e-3	2.1141e-2
a3	-8.876e-4	-1.8216e-3
a4	-4.271e-5	-2.1893e-5
Correlation Coefficient	1.000	-

These results are plotted in Figure 24 in which Capps' curve was overlaid on the regression curve obtained from the flexural experiment. We may conclude that the deviation between the two curves is greater than the experimental uncertainty of the data. Therefore, no definite conclusion can be made from this comparison as there are too many possible reasons for the deviation. The samples are not be identical in every aspect, namely, in preparation and curing and hence the assumption that a_T is the same in our sample may not be true. It might be advised to obtain a sample previously tested by a more conventional method such as Capps' [Ref. 16] and collect data using the technique outlined in this study.

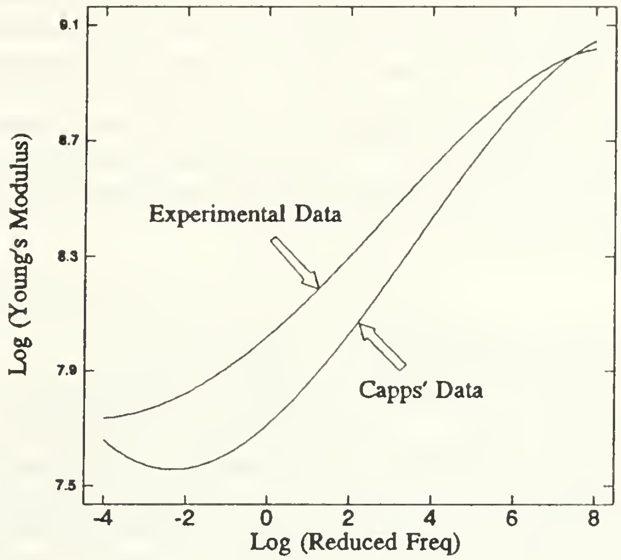


Figure 24. Comparison of experimental data with data from Capps.

VI. CONCLUSIONS AND RECOMMENDATIONS

The purpose of the research reported in this thesis was the extension of the free-free resonant bar technique described by Garrett [Ref. 3], which measured the shear and Young's moduli of elastic materials, to include the measurement of complex moduli of viscoelastic materials, particularly those materials which are important in the fabrication of hydrophones.

A. LOSS MODULUS MEASUREMENT TECHNIQUE

Since much of the utility of the free-free resonant method is due to its simplicity, both in the acquisition and analysis of the data based on measurement of the frequencies of the resonance modes of the sample, a simple extension of the method was devised for determining the loss tangent. This was accomplished by using the in-phase output of the phase sensitive detector to determine loss while the quadrature (out-of-phase) component was integrated and feed back to a voltage controlled oscillator to maintain the system at resonance. The validity of the relation used to convert in-phase output voltage to loss tangent (or its inverse, the resonance quality factor, Q) was verified by obtaining pole-zero curve fits to the entire resonance response curves as a means of independently determining the loss tangent. The experiment dependent (but temperature independent) conversion factor was found to be constant to within a few percent for the samples which were investigated.

Due to the interest in the measurement of loss modulus of polymeric samples, the contribution to the loss due to the sample suspension system, *e.g.*, rubber bands, were quantified by measuring the change in quality factor as a function of position of the sample suspension points. This was done with a low quality factor ($\approx$20) elastomeric sample using a pole-zero curve fit and with a high quality factor (≈1000) metallic sample using a free oscillation decay time measurement. Both techniques unambiguously established that the suspension losses were minimized when the sample was suspended at vibration nodes and that the maximum effect on the measured loss modulus due to the suspension system losses for elastomeric samples with quality factors less than 20 was less than 1%. For samples with intrinsic quality factors of order 1000, the suspension losses could in the worst case be as large as 40% as the support system is currently configured.

B. MODULI OF VISCOELASTIC SAMPLES

The technique was used successfully to measure the elastic moduli (both shear and Young's) and loss tangent for three elastomeric samples (Uralite 3130, PR1592, and PMMA) over a temperature range of -17°C to +85°C. The measured data for PR1592 and PMMA were converted to master curves using the frequency-temperature shift factors for those materials from the published literature. Over that temperature range, the PR1592 sample exhibited a complete viscoelastic transition with a peak in the loss tangent and an inflection point in the shear modulus which were observed at the same value of reduced frequency to within experimental error as would be expected from a simple viscoelastic model.

The absolute value of the Young's modulus for PR1592 differed from the master curve for that substance measured by NRL-USRD by an amount which exceed experimental error. The cause of this discrepancy has not yet been determined. One possible reason is that the samples were not of identical composition (molecular weight, cure time, *etc.*). We hope that this discrepancy can be resolved in the future by an exchange of samples between NPS and NRL-USRD.

C. ADVANTAGES OF THE FREE-FREE RESONANT TECHNIQUE

One conventional technique for making the measurement of storage and loss moduli involves the longitudinal excitation of a rod-shaped sample at one end by an electrodynamic shaker table and the detection of the rod response at the other end by a piezoelectric accelerometer. The complex transfer function thus obtained is used to derive the Young's modulus of the sample. This is accomplished by solving a complex transcendental equation which results from the fact that the mass of the accelerometer is a non-negligible fraction of the sample mass and the fact that the data obtained is, in general, at frequencies below resonance. The conventional technique also only obtains the Young's modulus. A different set-up, sample, and transducers are required to measure the shear modulus.

The free-free resonant bar technique is far simpler and all of the advantages discussed by Garrett [Ref.3] for this technique when used in the measurement of the shear modulus also apply to the measurement of the loss modulus. These include (1) the simplicity of the conversion of resonance frequency to modulus since the mass loading due to the transducers is small; (2) the fact that the transducers, consisting only of magnet wire, are so inexpensive that they can be left on the sample; and most importantly, (3) the ability to selectively and strongly excite all three modes of the bar (longitudinal, torsional, and flexural) and detect them with a high value of signal-to-noise using the same transducer. This ability to measure all three modes means that (4) both the Young's and shear moduli are available from the same apparatus and (5) there are two modes which yield values for Young's modulus so there is an intrinsic self-consistency check. The use of a phase sensitive detection scheme allows (6) the resonance to be tracked automatically and continuously by using the quadrature signal in a feed back circuit to maintain the bar at resonance as the temperature of the sample is varied. This thesis established that the in-phase signal can also be used to (7) automatically and continuously track the loss tangent as a function of temperature.

D. DISADVANTAGE OF THE FREE-FREE RESONANT TECHNIQUE

At the present time there seems to be only one significant disadvantage to this modulus measurement method in comparison with the conventional transfer function method described by Capps [Ref. 16]. This problem arises when one attempts to determine the temperature-frequency shift factor that is required to present the modulus data in the master curve format. In its present implementation, the free-free resonant technique described in this thesis provides modulus data at resonance frequencies which necessarily change with changing temperature. The determination of the shift factor is simplified if the modulus is obtained at fixed frequencies and a variety of temperatures.

In principle, the free-free resonant technique can provide the modulus at several frequencies for each temperature since more than one resonant mode can be observed (four modes were tracked for torsional vibrations of PR1592) but at this time we have not been successful in developing an algorithm which can extract the shift parameter from these multiple modes. One could, of course, obtain a variety of frequencies at all temperatures by using samples of different length but this would increase the measurement complexity by requiring more than one sample.

E. RECOMMENDATION FOR FURTHER STUDY

Based on the conclusions reported in this chapter, the two most interesting and important follow-on research problems would have to be (1) the derivation of an algorithm for the extraction of the frequency-temperature shift factor for the modulus measured by the temperature dependance of the fundamental resonance and its next few overtones and (2) a "round robin" calibration of "standard" samples using both the free-free resonant technique and the conventional transfer function technique.

APPENDIX A. CONFERENCE PAPER PRESENTED IN SPIE CONFERENCE "FIBER OPTIC SMART STRUCTURES AND SKIN III" IN SAN JOSE, SEPTEMBER 1990.

Nondestructive Dynamic Complex Moduli Measurements Using a Michelson Fiber Interferometer and a Resonant Bar Technique

David A. Brown, Beng-Hock Tan, and Steven L. Garrett
Naval Postgraduate School, Physics Department, Code PH/Gx
Monterey, CA 93943

ABSTRACT

An optical fiber, used as a leg of a Michelson interferometer, is cast into a long cylindrical bar of E-CAST F-82 epoxy[1]. The bar can be selectively excited in any of its lowest flexural, torsional, and longitudinal modes. The interferometer is used to detect the resonant modes of the "free-free" bar and from these modes both the Young's and shear elastic moduli are determined. The complex modulus is determined by measuring the quality factor (Q) for each resonant mode. The measurement technique is entirely nondestructive and yields results of the two independent moduli with the same transducers.

1. INTRODUCTION

This article involves the use of fiber-optic sensors in the non destructive resonant determination of elastic moduli of epoxies. A "free-free" bar is selectively excited in its flexural, torsional, and longitudinal vibrational modes using a transducer consisting of coils of magnet wire placed in the magnetic field created by a pair of permanent magnets, the details of which are covered in an article entitled "Resonant Acoustic Determination of Elastic Moduli"[2]. A commercially available apparatus[3] was used to excite the modes of a bar which had embedded in it an optical fiber acting as the sensing leg of an interferometer. The bar is placed on a pair of soft rubber bands so that the ends are free to move. The phase modulations induced in the optical fiber are converted interferometrically into intensity modulations at the coupler location. The output of the interferometer at the photodetector is monitored to accurately determine the resonant frequency (and its overtones) of the particular mode of excitation of the bar. The square of the frequencies of the flexural and longitudinal resonant modes are proportional to the Young's modulus and the square of the frequency of the torsional modes is proportional to the shear modulus. The quality factor, or Q, of the resonant modes is equal to the ratio of the real to imaginary parts of the complex moduli and the inverse of the characteristic loss tangent, tan δ. Since the measurement technique is resonant, the signal to noise ratios are typically very high and the modulus that is obtained is a dynamic complex modulus at the frequencies corresponding to the fundamental bar resonance and its overtones. The modes are also determined by a second coil electrodynamically as described in reference 2.

2. EXCITATION AND DETECTION

The differential Lorentz, $d\vec{F}$, force produced on a segment of wire, $d\vec{l}$, carrying a current, I, in a static magnetic field, $\vec{B}$, is given by

$$d\vec{F} = I\, d\vec{l} \times \vec{B}. \tag{1}$$

Longitudinal, torsional, or flexural forces can be generated in order to selectively excite each of the three vibrational modes with the apparatus pictured in Figure 1. The particular mode excited depends on the relative positioning of the wire coils carrying the current, I, and the direction of the magnetic field. Typically the magnetic field direction and strength created by the pair of permanent magnets as well as the current driven through the coil of wire are constant and independent of frequency. When the frequency of the oscillator driving the wire coil is varied the bar is excited in its characteristic resonant modes of vibration. The detection of these modes is typically an easy task and can be accomplished by placing a second wire coil at the opposite end of the bar within a magnetic field created by a second pair of permanent magnets. The output of this coil of wire transducer is an EMF (voltage) which is proportional to the change in magnetic flux linking the coil and is given by

$$V = -\frac{d}{dt}\int_s \vec{B} \cdot \vec{n}\, dA \tag{2}$$

For a small segment of wire moving with velocity, $\vec{u}$ in a magnetic field $\vec{B}$, the induced EMF is given by

$$V = \vec{B}\ \ \vec{l} \times \vec{u} \tag{3}$$

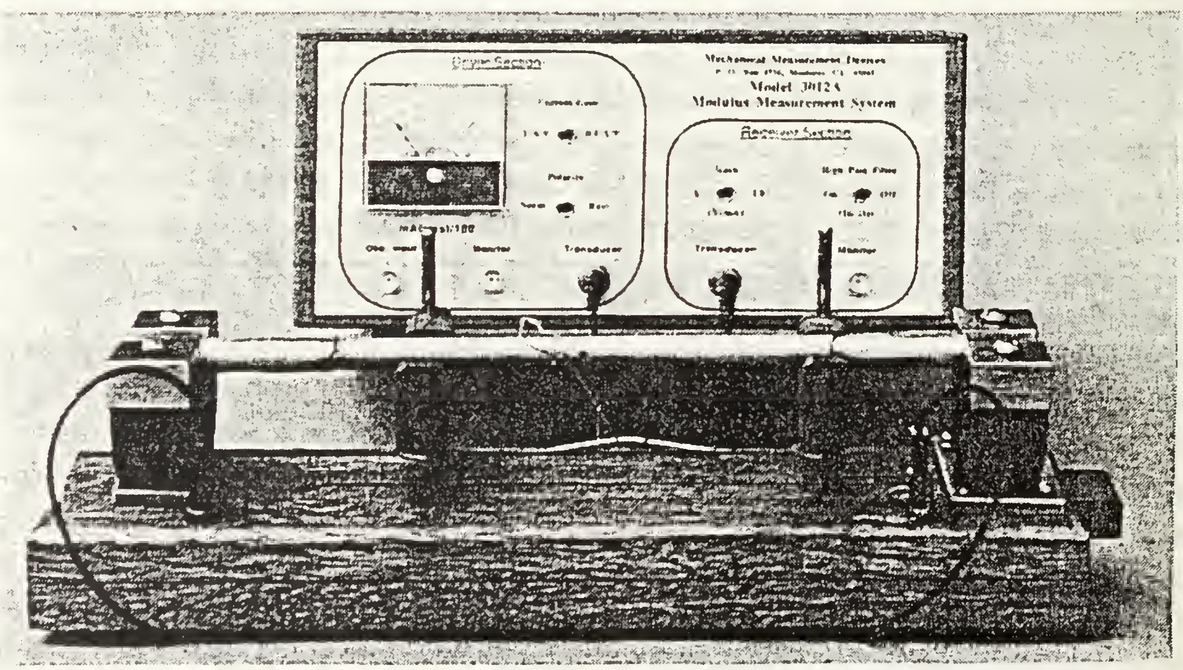


Figure 1. The MMD measurement apparatus[3] used to electrodynamically excite and detect the flexural, longitudinal, and torsional modes of a bar in order to determine the shear and Young's elastic moduli.

The resonant vibrational modes can also be detected interferometrically due to the sinusoidally excited strain induced phase shifts in the leg of the interferometer. The output of a pigtailed single mode laser (Sharp LT010, 818 nm) is delivered to a 2 x 2 fiber optic splitter/coupler where it is divided into two separate legs of a Michelson interferometer. One leg is cast axially a constant radial distance from the center of the rod and the other acting as a reference placed on the lab bench. The interferometer is cleaved at the end of the rod so that the coherent light reflects and combines interferometrically at the coupler which is characteristic of a Michelson interferometer. The resulting characteristic fringe pattern is observed with an oscilloscope from the output of a photodetector as illustrated in the measurement setup in Figure 2.

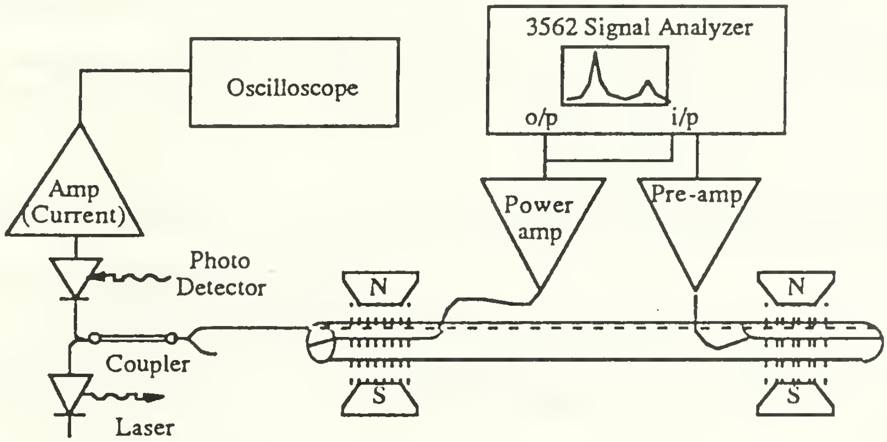


Figure 2. Illustration of the measurement setup for the electrodynamic excitation and both electrodynamic and interferometric detection of the modes of a bar.

3. THEORETICAL RESONANCE FREQUENCY

Once the resonances have been determined the appropriate moduli, Young's, E, or shear, G, can be determined from the equations in this section provided that the dimensions and density of the bar can be measured. The resonance frequencies will also depend on the boundary conditions which for this apparatus is "free-free" corresponding to zero stress and zero moment at both ends.

A uniform, cylindrical rod-shaped sample of a homogeneous, isotropic solid having circular cross-sectional diameter, d, and length, L, which is significantly greater than its diameter, will propagate three independent waves if their wavelengths, λ, are much greater than d. The displacements associated with the longitudinal and torsional modes satisfy a partial second-order wave equation, and for a free-free boundary condition, the resonances are harmonically related. The Young's modulus can be expressed in terms of these parameters as

$$E = 4\rho L^2 \left(\frac{f^L_n}{n}\right)^2 \qquad (4)$$

where n is a positive integer. Similarly, the free-free boundary condition leads to a series of harmonic torsional modes whose frequencies, f^T_n, are related to the shear modulus by

$$G = 4\rho L^2 \left(\frac{f^T{}_n}{n}\right)^2 . \qquad (5)$$

The measurement of the flexural mode is not necessary but it does provide a second estimate for the Young's modulus and its fundamental frequency is typically an order-of-magnitude lower than the longitudinal modes. The flexural mode is also strongly excited by this electrodynamic transduction scheme so it is easy to observe.

Unlike the torsional and longitudinal modes, the flexural waves of the bar obey a fourth-order differential equation and the flexural wave phase speed is dispersive. The application of "free-free" boundary conditions in this case leads to a series of modes which are overtones but not harmonics. The Young's modulus of the rod can be expressed in terms of the flexural modes as

$$E = \frac{1024}{\pi^2} \frac{\rho L^4}{d^2} \left(\frac{f^F{}_n}{n^2}\right)^2 . \qquad (6)$$

where n takes on the values 3.0112, 4.9994, 7, 9, 11...

4. CONCEPT OF A COMPLEX MODULUS

4.1 The Loss Tangent and Quality Factor

Many solids and most metals behave as nearly perfect elastic media and obey Hooke's Law. For the application of a dynamic force to these materials, there is a corresponding deformation that, in the linear limit, is proportional to the magnitude of, and in phase with, the applied stress. The ratio of the applied stress to the resulting normalized deformation or strain is therefore a characteristic property of the material which is termed the elastic modulus. The modulus of these metals may be independent of frequency over a large frequency range. If a material possesses sufficient damping characteristics, (or equivalently low Q's) energy can be dissipated as heat in each cyclic deformation resulting in a strain that is out of phase an angle δ with the applied stress. The characteristic elastic modulus can thus be represented as a complex quantity in phasor notation with magnitude G and phasor angle δ ,or as an in phase, G', and quadrature term, G" as[4,5]

$$G^* = Ge^{j\delta_o} = G' + j\,G'' \qquad (7)$$

where $G''/G' = \tan \delta_G$ and $j = \sqrt{-1}$. The loss tangent is related to the mechanical Q by the relation:

$$\tan \delta_G = G''/G' = \frac{1}{Q} \qquad (8)$$

To illustrate the concept of the complex modulus further, let us start with the familiar equation of motion for a damped driven oscillator

$$M\frac{\partial^2 \xi(t)}{\partial^2 t} + R\frac{\partial \xi(t)}{\partial t} + K\,\xi(t) = F(t) \qquad (9)$$

where ξ is the displacement from equilibrium, M is the mass of the oscillator, R is the resistive mechanical damping coefficient, K is the spring constant or characteristic stiffness, and F is the applied force. If the applied force is sinusoidal of frequency ω, the above equation is expressed as complex variables in the form

$$-\omega^2 M \xi^* + K\left(1+j\frac{\omega R}{K}\right)\xi^* = F^* \qquad (10)$$

where the coefficient of ξ^* (the effective stiffness term) can also be expressed as a complex variable[6]

$$K^* = K\left(1+j\frac{\omega R}{K}\right) = K\left(1+j\tan\delta\right). \qquad (11)$$

At a driving frequency coinciding with resonance, $\omega = \omega_0 = \sqrt{K/M}$, the tangent of the phase difference δ is inversely related to the quality factor, Q by

$$\frac{1}{\tan\delta} = \frac{K}{\omega_0 R} = \frac{\sqrt{KM}}{R} = \frac{\omega_0 M}{R} = Q. \qquad (12)$$

The quality factor also has the following common definitions

$$Q = \frac{\omega_0}{\omega_U - \omega_L} = \tfrac{1}{2}\,\omega_0 \tau \qquad (13)$$

where ω_u, ω_L are the frequencies above and below resonance for which the average power is 3 dB down relative to its value at resonance and τ is the decay modulus or characteristic time required for the free decay amplitude to decrease to 1/e of its initial value. The Q is also equal to the ratio of 2π times the mechanical energy stored in the oscillator to the energy dissipated per acoustic period.[7]

4.2 Quality Factor determination from pole-zero plots

The Q, and thus complex modulus, can also be found from a pole zero plot of the mechanical admittance of the oscillator as will be illustrated in this section by measuring the frequency response of the output, eqn. (3), (induced EMF) of the detection transducer (which is proportional to velocity) to the input force, eqn. (1), (which is typically constant).

Again considering the damped driven harmonic oscillator of frequency ω, and noting that the complex velocity and displacement are related by $u^* = j\omega\xi^*$, the complex admittance u^*/F^* (which is equal to the inverse of the complex impedance) is given by

$$Y^{*}(j\omega) = \frac{j\omega}{M\left[(j\omega)^{2} + \frac{R}{M}(j\omega) + \frac{K}{M}\right]} \tag{14}$$

The complex mechanical admittance is directly analogous to the the complex electrical admittance of an RLC circuit[8] with the familiar electrical quantities voltage, current, electrical resistance, inductance, and capacitance (V, I, R, L, C) corresponding to the mechanical quantities force, velocity, mechanical resistance, mass, and compliance or inverse stiffness (F, u, R, M, 1/K) respectively. Letting $j\omega = s$, we can factor the admittance in pole-zero format as follows

$$Y^{*}(s) = \frac{s}{M\left[s^{2} + \frac{R}{M}s + \frac{K}{M}\right]} = \frac{1}{M}\left[\frac{s}{(s-\gamma)\,(s-\gamma^{*})}\right] \tag{15}$$

where γ, γ^{*} are complex conjugates. Noting $\omega_0 = \sqrt{K/M}$, the characteristic roots are

$$\gamma = \frac{-R}{2M} + j\sqrt{\omega_0^2 - \left(\frac{R}{2M}\right)^2} \quad \text{and} \quad \gamma = \frac{-R}{2M} - j\sqrt{\omega_0^2 - \left(\frac{R}{2M}\right)^2}. \tag{16}$$

Thus the transfer admittance function has poles at γ and γ^{*} and a single zero at $\omega = 0$. Note that in this derivation we are only considering oscillatory solutions which correspond to $R/(2M) < \omega_0$. The pole zero plot is illustrated in Figure 3 and the poles are located on a circle of radius ω_0.

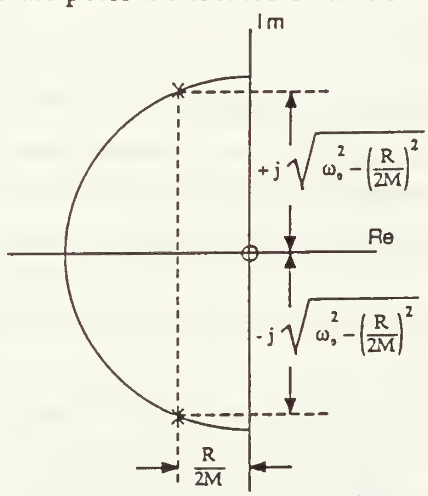


Figure 3. Pole zero plot of complex admittance function.

If we express the location of the poles as $\gamma = a + jb$ and $\gamma^{*} = a - jb$, then Q can be expressed as follows

$$Q = \frac{\sqrt{b^2 + a^2}}{-2a} \tag{17}$$

and the resonance frequency is equal to

$$\omega_0 = \sqrt{b^2 + a^2} \cong b\left(1 + \frac{1}{2}\, {a^2}/{b^2}\right) \approx b \qquad (18)$$

where the first approximation is from the binomial expansion theorem and the second approximation is valid for low to moderate damping.

6. MEASUREMENTS AND RESULTS

A single optical fiber is used as the leg of a Michelson interferometer, and was cast into a long bar of E-CAST F-28 (1.24 cm diameter, 30.36 cm length, and density of 1120 Kg/m^3) at an off axis distances of approximately 6.0 mm. As the rod is sinusoidally driven with either longitudinal, transverse, or torsional stresses, strains will be produced in the leg of the interferometer which result in phase shifts relative to the unattached unstrained reference leg of the interferometer.

The flexural, torsional, and longitudinal modes were clearly detected from the transducer coil output and interferometric phase modulated output. The first three torsional resonances occurred at 1485, 3075, and 4684 Hz. The first two flexural resonances occurred at 182.3 and 514.7 Hz. The first three longitudinal resonances occurred at 2535, 5243, and 7712 Hz. These resonances were measured at an average room temperature of 24 °C. A typical interferometric output and electromagnetic coil output pair for the flexural fundamental resonance mode is illustrated in Figure 4. From eqn. (4-8), the complex shear and Young's modulus corresponding to these resonances are tabulated in Table 1 for the bar.

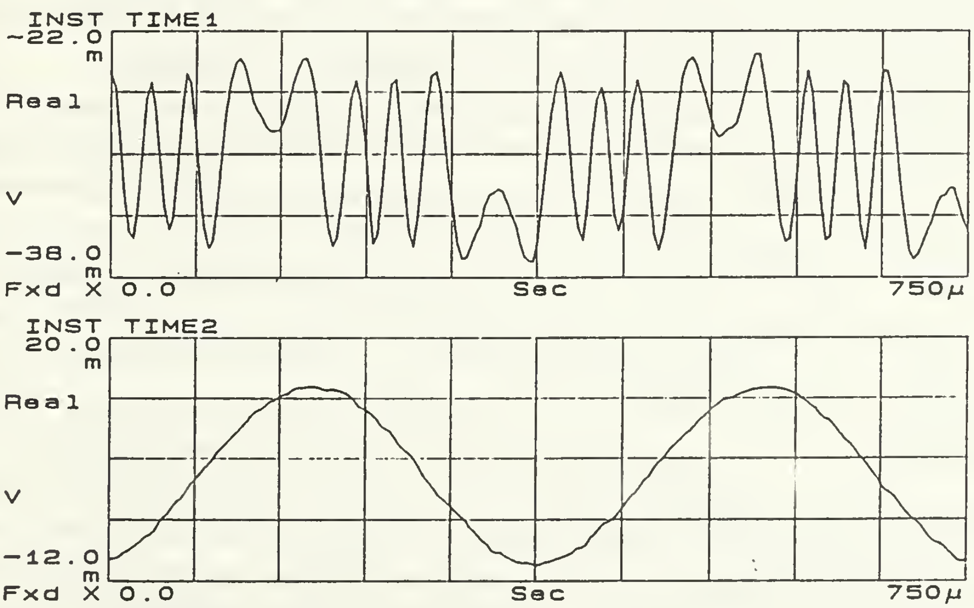


Figure 4. Typical interferometric output (Top) and corresponding transducer coil output (Bottom) at resonance for the fundamental flexural mode of the E-CAST bar.

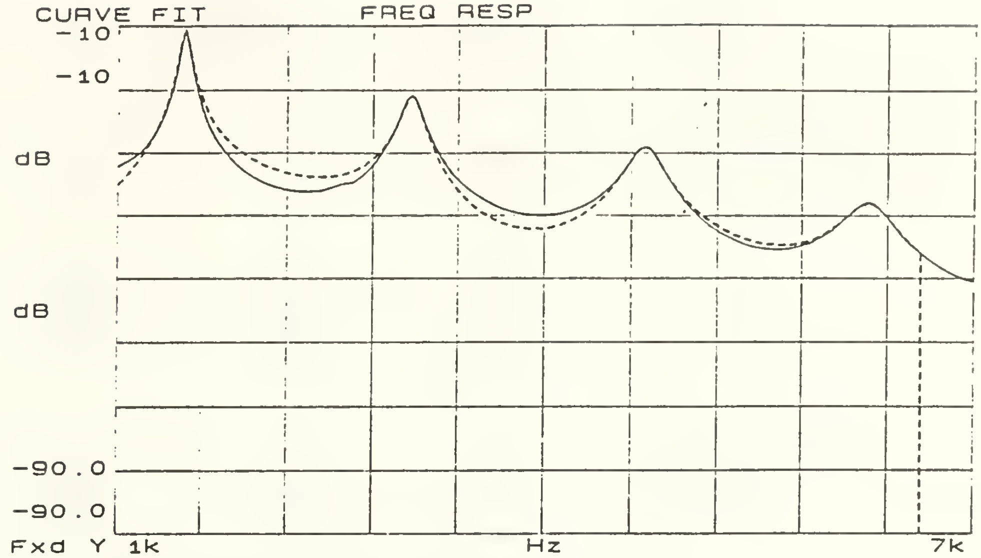
Mode # [n]	Frequency $[f_n]$ (Hz)	Freq/Mode # $[f_n/n]$ (Hz)	Quality factor [Q]	Loss factor [δ] (%)	Modulus (Pa)
1. Torsional					
1	1485	1485	20.1	4.97	
2	3075	1538	19.8	5.05	
3	4684	1561	19.1	5.24	(shear modulus G*)
	Average	1528	19.7	5.09	$0.935 \times 10^9 (1 + j .0509)$
2. Flexural					
$(3.0112)^2$	182.3	20.11	30.0	3.33	
$(4.9994)^2$	514.7	20.59	30.4	3.29	(Young's modulus Y*)
	Average	20.35	30.2	3.31	$2.66 \times 10^9 (1 + j .0331)$
3. Longitudinal					
1	2535	2535	21.6	4.63	
2	5243	2622			
3	7712	2571	____	___	(Young's modulus Y*)
Average		2576	21.6	4.63	$2.74 \times 10^9 (1 + j .0463)$

Table 1. Summary of the frequencies of the modes of vibration of the sample bar described in the text.

After using the HP3562 (dynamic signal spectrum analyzer) to sweep through the appropriate frequency range in order to excite each mode of vibration as illustrated in the measurement setup diagram in Figure 2, the resonances were determined from the displayed frequency response and verified by manually adjusting the oscillator for greater resolution. The quality factor, or Q's, for each mode were obtained by measuring the upper and lower 1/e (or -3dB) points on each side of resonance by adjusting the local oscillator. The Q's listed in Table 1 were obtained from this method.

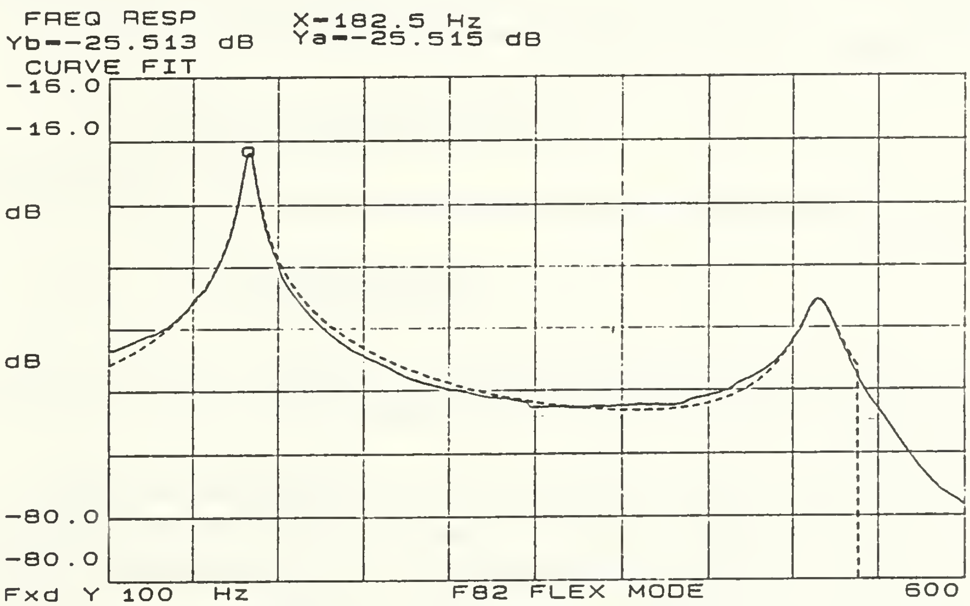
Since the HP3562 also possesses pole-zero curve fitting features, the resonances and quality factors were determined from the HP3562 generated curve fit parameters according to eqns. (17) and (18) derived earlier. It should be noted that the poles and zeros from the HP3562 generated plot are in Hertz and not in radians as suggested in eqns. (17) and (18). The frequency response of the detection wire coil transducer to the input drive for the torsional mode of vibration, the corresponding HP3562 curve fit response, and the list of poles and zeros are illustrated in Figure 5. The first four torsional resonances, which are harmonically related, are clearly identifiable. The frequency response of the flexural mode of vibration, the corresponding HP3562 curve fit response, and corresponding table of poles and zeros are illustrated in Figure 6. The corresponding resonance frequencies and quality factors determined from these poles and zeros are tabulated in Table 2. Due to temperature changes in the room, the measured resonance frequencies do differ for different measurements and thus more accurate temperature control by means of an environmental chamber is needed for measurement-to-measurement repeatability.

Having obtained the two independent moduli, the set of elastic constants for the isotropic material can be determined, *i.e.* the Poisson's ratio, ν , is found to be 0.444 from[4], $\nu = [E/(2G)] - 1$, and using the average value for the Young's modulus of $E = 2.7 \times 10^9$ Pa and the shear modulus of $G = 0.935 \times 10^9$ Pa.



	POLES 8	ZEROS 10
1	-37.944 ±j 1.4731k	172.644
2	-70.1106 ±j 3.07572k	19.2379k
3	-113.672 ±j 4.69109k	1.08758k ±j 3.57851k
4	-162.413 ±j 6.27439k	-1.05105k ±j 3.75323k
5		1.03638k ±j 6.16017k
6		-1.21271k ±j 6.48818k

Figure 5. Frequency response of the transducer coil output for the torsional modes of the bar. The dotted line is a generated HP3562 frequency response with corresponding curve fit parameters (poles and zeros) listed below.



	POLES 4	ZEROS 6
1	-3.58457 ±j 183.081	151.287
2	-9.16888 ±j 515.869	260.823 ±j 404.557
3		-67.4989 ±j 528.94

Figure 6. Frequency response of the transducer coil output for first two flexural modes of the epoxy bar. The dotted line is a the HP3562 curve ft frequency response with corresponding curve fit parameters (poles and zeros) listed below.

Mode # [n]	Frequency $[f_n]$ (Hz)	Freq/Mode # $[f_n/n]$ (Hz)	Quality factor [Q]
Torsional			
1	1474	1474	19.42
2	3077	1539	21.94
3	4692	1564	20.64
4.	6276	1569	19.32
	Average	1536	20.34
Flexural			
$(3.0112)^2$	183.1	20.11	35.54
$(4.9994)^2$	516.0	20.59	38.14
	Average	20.35	36.86

Table 2. Resonance frequencies and Q's determined from the pole zero plots in Figures 5 and 6 and the eqns. (17) and (18).

6. CONCLUSIONS

A resonant method for determining the complex Young's and shear modulus of elasticity has been presented that uses coils of wire to excite and detect vibrational modes of a bar. For detection, an optical interferometer, whose leg is cast in the material under investigation, can also be used to accurately detect the three resonant modes via strain induced phase modulations.

7. ACKNOWLEDGEMENTS

This work was supported by the Naval Postgraduate School Direct Funded Research Program.

8. REFERENCES

1. United Resin Corp., E-CAST F-82, Warren, MI 48093.
2. S. L. Garrett "Resonant acoustic determination of elastic moduli", J. Acous. Soc. Am., **88** (1), 210-221 (1990).
3. Mechanical Measurement Devices, P.O. Box 8716, Monterey, CA 93943.
4. H. T. Loeser, "Principles of Sonar Installation", Naval Underwater Sys. Cntr., Doc. # 6059, 1984.
5. R. N. Capps, "Elastomeric Materials for Acoustical Applications", Naval Research Laboratory (USRD Doc. # 61153-N) Report Date: Sept. 15, 1989.
6. P. M. Morse, *Vibration and Sound* (Am. Inst. of Phy., New York), 25.
7. W. T. Thompson, *Theory of Vibration with Applications*, 2nd ed., Prentice-Hall Inc., Chapt. 3.
8. M. E. Van Valkenburg, *Network Analysis*, 3rd ed., Prentice-Hall Inc., Chapt. 13.

APPENDIX B. MATERIAL SPECIFICATION SHEETS

1. URALITE 3130

2. PR1592

HEXCEL chemical products
RESIN CHEMICALS GROUP

URALITE® 3130

URETHANE CASTING ELASTOMER

80-85 Shore A

25-30 Shore D

TECHNICAL DATA BULLETIN

- No moisture sensitivity
- Excellent hydrolytic stability (Reversion Resistance)
- No TDI, no 4,4′-Methylene-bis-(2-chloroaniline)
- Fast cure, quick demolding
- High abrasion resistance
- Low Viscosity
- Good Electrical Properties
- Good Adhesion to many substrates

DESCRIPTION

Uralite 3130 is a two component, natural amber or black urethane casting elastomer. This tough room temperature mixing and curing system has excellent handling characteristics. Uralite 3130 is a middle of the hardness range, general purpose, versatile Uralite elastomer. It does not exhibit typical moisture sensitive characteristics of most urethane elastomers.

USES:

- Electrical and Electronic Encapsulating
- Molds and Mold Facings
- Metal forming pads
- Flexible snakes
- Gaskets
- Abrasion resistant parts

PROPERTIES:

	Test Method	Value	(Metrics)
Shore Hardness A/D	ASTM D 2240-68	80-85/25-30	
Viscosity Part A — cps	ASTM D 2393-71	3400	
Viscosity Part B — cps	ASTM D 2393-71	120	
Mixed Viscosity — cps	ASTM D 2393-71	2000	
Tensile Strength — psi (kg/cm^2)	ASTM D 412-68	2750	(193)
Elongation — %	ASTM D 412-68	250	
Tear Strength — pli (kg/cm)	ASTM D 624 Die C	250	(45)
Dielectric Strength — step @ 77°F (25°C), volts/mil	ASTM D 149-64	240	
Dielectric Constant — @77°F (25°C)	ASTM D 150-54T		
10^6 Hz		5.6	
10^3 Hz		7.2	
Volume Resistivity — @77°F (25°C) @1000V, ohm-cm	ASTM D 257-70	1×10^{13}	
Surface Resistivity — @77°F (25°C) 1000V, ohms	ASTM D 257-70	2×10^{13}	

(over)

PROPERTIES: (Continued)

	Test Method	Value	(Metrics)
Insulation Resistance — @77°F (25°C) ohms after 28 days @ 95°F (35°C) 95% RH	WE ATS612	1×10^{11}	
Pot Life — min. @ 77°F (25°C)	ASTM D 2471-71	14	
Shrinkage - in/in (mm/mm)	ASTM D 2566-69	0.0016	
Density	ASTM D 792-66		
Cured Compound lbs/in³ (g/cm³)		0.039	(1.07)
Part A lbs./gal. (g/cm³)		8.58	(1.03)
Part B lbs./gal. (g/cm³)		9.15	(1.10)
Demolding Time — hrs @ 77°F (25°C)		4	
Demolding Time — hrs @ 175°F (79°C)		1	
Complete Cure — days @ 77°F (25°C)		2 - 4	
Complete Cure — hrs. @ 175°F (79°C)		2 - 3	
Color		Amber or Black	
Ratio (By Weight):			
Part A		100	
Part B		30	
Ratio (By Volume):			
Part A		100	
Part B		28	

These physical properties are representative of typical values obtained by tests conducted in the Chemical Products Division laboratory.

STORAGE:

Uralite 3130 should be stored in a cool dry area. Avoid temperatures above 90°F and below 65°F. Always blanket Uralite 3130 with dry nitorgen or 8440 Inert Blanketing Gas and reseal container after use.

SURFACE PREPARATION SUGGESTIONS:

Porous materials, such as plaster and wood, must have all surfaces that come in contact with Uralite 3130 well-sealed with a sealer which is compatible with urethane (acrylic sealers are suggested). After sufficient drying time, approximately thirty (30) minutes after last coat, the final surface preparation consists of the application of a release agent such as Partingkote® 8302 (wiping off excess) to accomplish a complete and uniform release coating.

MIXING:

Ratio: Parts by Weight Part A — 100, Part B — 30

Ratio: Parts by Volume Part A — 100, Part B — 28

Weigh both components into same container and stir slowly for 2-4 minutes, scraping the sides and bottom of container periodically to include unmixed material which may adhere to these surfaces. Care must be taken to avoid whipping air into mixture. Pour the thoroughly mixed Uralite 3130 onto the prepared surface and allow to cure. Working pot life of Uralite 3130 is approximately 14 minutes.

CURING:

Near ultimate physical properties are normally attained after 2 days at room temperature (77°F). Curing of Uralite 3130 may be accelerated by heating for 1-2 hours at 175°F. Demolding can be accomplished after 4 hours at room temperature.

PACKAGING:

UNIT DESIGNATION	PART A	PART B	UNIT NET WEIGHT
12 Qt. Pack (pre-weighed)	12-One Qt. Cans	12-½ Pint Cans	22 lbs. 13.12 ozs.
Pail Pack	5 Gal. Pail	2½ Gal. Can	52 lbs.
Drum Pack	55 Gal. Drum	30 Gal. Drum	585 lbs.

CAUTION:

FOR INDUSTRIAL USE ONLY.

This product contains an isocyanate based prepolymer, amines and heavy metal catalysts which are harmful if swallowed. It does not contain toluene diisocyanate or 4,4' methylene bis-(2-chloroaniline). It may cause burns or skin irritation. Use only in a well ventilated area. Protect skin and eyes from contact and avoid inhalation of vapors.

Should skin contact occur, wash with soap and water. For eye contact, flush with water immediately and obtain medical attention. If swallowed, drink water, induce vomiting and contact a physician immediately.

HEXCEL CORPORATION, RESIN CHEMICALS GROUP 818
20701 NORDHOFF STREET, CHATSWORTH, CALIFORNIA 91311 • (213) 882-3022

807 Printed in U.S.A.

AEROSPACE/ELECTRONIC PRODUCTS

PR-1592

POTTING AND MOLDING COMPOUND

Use

Especially formulated as a high hardness molding compound for electrical cables and/or as a potting compound for electrical connectors where resistance to cold flow, fexibility, high tensile strength, and exposure from −70°F to 275°F for extended periods are required.

Description

PR-1592 is a noncracking, chemically curing, polyurethane compound which is supplied in Amber or Black and in two-part quantities or premixed and frozen in plastic cartridges. PR-1592 cures at 180°F to a tough, flexible, cold flow-resistant, high tensile strength rubber with a Shore A hardness of 85. PR-1592 will cure at 75°F, but the resultant physical properties will be lower than when heat cured. Properly cured PR-1592 is designed to withstand temperatures as high as 275°F for extended periods without blowing, deterioration or loss in electrical properties, and has excellent flexibility at −70°F.

The viscosity of PR-1592 allows the material to be degassed easily when supplied in two part units and provides for excellent flow of characteristics in encapsulating, molding and potting applications.

PR-1592 must be used with a primer on metal, neoprene and polyvinyl chloride surfaces.

Specifications

PR-1592 meets the requirements of MIL-M-24041C Category B

Application Properties (Typical)

Color		
Part A	Dark Amber or Black	
Part B	Straw	
Mixing Ratio	Part A:Part B 53:100 by weight	
Nonvolatile Content	99%	
Viscosity (Brookfield Spindle #3 @ 10 rpm)		
Two-part unit	200 poises	
Premixed, frozen	700 poises	
Application Life		
Two-part unit		
Time to 2500 poises	2 hrs.	@ 75°F
Premixed, frozen		
Time to 2500 poises	1 hr.	@ 75°F
Mold Release Time	2 hrs.	@ 180°F
Cure Time		
To 75 Shore A hardness	7 days	@ 75°F or
	6 hrs.	@ 180°F
To 85 Shore A hardness	21 days	@ 75°F or
(Ultimate cure)	16 hrs.	@ 180°F

NOTE: The above times are at the temperature indicated. Therefore, it is necessary to allow time for the mass of material, molds, etc. to reach the temperature.

Performance Properties (Typical)

(Cured 16 hours at 180°F)

Color	Dark Amber or Black
Specific Gravity	1.08
Hardness, Shore A	85
Volume Shrinkage	4%
Tensile Strength	6000 psi
Ultimate Elongation	425%
Tear Strength (Die C)	320 lbs./in.
100% Modulus	600 psi
Compression Set (ASTM D 395, Method B) 22 hrs. @ 158°F	40%
Ozone Resistance	Conforms
(Tested in accordance with MSFC-SPEC 202B)	
Moisture Absorption	2.4%
(Tested in accordance with MIL-M-24041)	
Flame Resistance	
Current overload; 55 amps DC applied 2½ mins. through #16 wire	No ignition
Flame exposure; ASTM D 635-63	Self-extinguishing

(Continued on Page 2)

SUPERSEDES MARCH 1987
DATE ISSUED SEPTEMBER 1987

PRODUCTS RESEARCH & CHEMICAL CORPORATION
5454 SAN FERNANDO ROAD
POST OFFICE BOX 1800
GLENDALE, CALIFORNIA 91209
AREA CODE (818) 240-2060

410-416 JERSEY AVENUE
GLOUCESTER CITY, NEW JERSEY 08030
AREA CODE (609) 456-5700

01-T-0:0
PR-1592

Performance Properties *(Continued from Page 1)*

Hydrolytic Stability, Hardness Change	
After 120 days @ 158°F, 95% RH	−15%
Adhesion, Peel Stength	
Aluminum (Primed with PR-420)	40 piw
Neoprene (Primed with PR-1523-M)	25 piw
PVC (MEK tackified)	28 piw
Fungus Resistance (Tested in accordance with MIL-E-5272A)	Non-nutrient

Electrical Properties (Typical)

(Cured 16 hrs. @ 180°F)

Arc Resistance	150 seconds	
Dielectric Strength	300 volts/mil	
Dielectric Constant		
At 1 KHz @ 75°F	6.5	
At 1 MHz @ 75°F	4.6	
Power Factor		
At 1 KHz @ 75°F	0.08	
At 1 MHz @ 75°F	0.06	
Insulation Resistance		
At 75°F	5×10^5 megohms	
At 250°F	150 megohms	
Resistivity	At 75°F	At 250°F
Volume, ohm-cm	1×10^{12}	4×10^9
Surface, ohms	1×10^{13}	8×10^{10}

NOTE: The above application, performance and electrical property values are typical for the material, but are not intended for use in specifications or for acceptance inspection criteria because of variations in testing methods, conditions and configurations.

Purchasing Data

PRODUCT DESIGNATION

When ordering this product, designate PR-1592 and color as follows: PR-1592 Amber or PR-1592 Black.

NOTE: Refer to "Surface Preparation" for primer requirement.

STANDARD PACKAGING

Two-Part Units

Designation	Part A Container	Part B Container	Units per Case
40 fl. oz. unit	1-pt. can	1-qt. can	9
160 fl. oz. unit	½-gal. can	1-gal. can	4

NOTE: The unit designates the total fluid ounce content of Part A and Part B (128 fluid ounces per gallon). Standard units are furnished with a premeasured quantity of Part A and Part B, individually packaged.

Frozen Cartridges

Designation	Approximate Contents	No. Cartridges per Case
2½ oz. cartridge	2¼ fl. oz.	72
6 oz. cartridge	5¾ fl. oz.	36
12 oz. cartridge	11½ fl. oz.	36

PRIMER DESIGNATION

When ordering primer, designate PR-420, PR-1523-M or PR-1543 as required under "Surface Preparation."

STANDARD PACKAGING

PR-420 is packaged as follows:

Designation	Part B Container	Total Contents	No. per Case
# 7 kit	½-pt. can	7 fl. oz.	16
#14 kit	1-pt. can	14 fl. oz.	16

NOTE: The kit number designates the total fluid ounce content of Part A and Part B. Kits are furnished with a premeasured quantity of Part A and Part B individually packaged. The kits are designed so that adequate space is available in the Part B container for addition of Part A and mixing.

PR-1523-M and PR-1543 are packaged ready to use in the following containers:

Designation	Container	Contents	No. per Case
2 fl. oz.	2 fl. oz. bottle	2 fl. oz.	6
½ pint	½-pint bottle	8 fl. oz.	12
One pint	1-pint bottle	16 fl. oz.	12

Surface Preparation

CLEANING

Connectors or other metal surfaces must be free of grease, oil and wax in order to insure good adhesion. Use oil-free solvent applied with a small brush or oil-free cloths for cleaning (reclaimed solvents should not be used). Premixed cleaners are commercially available. Do not expose wire insulation and inserts to the cleaning solvent beyond the time necessary for adequate cleaning.

APPLICATION OF PRIMER

For maximum adhesive strength between PR-1592 and the material to which it is to be bonded, the following surface preparations are required:

NOTE: Do not dip priming brush into primer supply. To maintain an uncontaminated primer supply, pour a small portion of primer into a clean container from which it should be used. Reseal primer supply immediately after portion has been removed.

(a) Metal

Metal must be primed with PR-420. Thoroughly mix 1 part of Part A with 6 parts of Part B by volume. Do not mix more than can be used within a 4 hour period. Brush a thin film of mixed PR-420 on all inside surfaces of connectors and on wire, but not on the insulation. Let primer dry for 1 hour at 75°F. If primer becomes contaminated, reclean primed surface lightly with methyl ethyl ketone and dry. Stripping the primer from the connector and repriming is not necessary.

(b) Neoprene
To obtain good adhesion to neoprene insulation, the surface should be abraded with a suitable abrasive to remove grease, oil, wax or mold release. Remove rubber particles with a dry oil-free brush.

Apply a liberal coat of PR-1523-M to the clean neoprene surface by brush and allow to dry for approximately 30 minutes at room temperature. After 30 minutes drying time, wipe off excess PR-1523-M primer with a clean, gauze pad and start the potting or molding procedure. Drying time of PR-1523-M should not exceed 4 hours at room temperature before potting or molding. If primed surface becomes contaminated or potting or molding is not accomplished within 4 hours after application of PR-1523-M, buff neoprene and repeat priming procedure.

NOTE: PR-1523-M is hygroscopic and must be kept free of moisture. When PR-1523-M hydrolyzes, a dark grainy precipitate is formed decreasing the primer usefulness. Material containing precipitate should be tested to determine that adhesion is satisfactory before using.

(c) Polyvinyl Chloride
To obtain good adhesion to polyvinyl chloride insulation, the surface should be made tacky with methyl ethyl ketone. The use of a primer may be necessary only with some formulations of polyvinyl chloride. Therefore, it is suggested that tests be made to determine the adhesive strength of PR-1592 to the polyvinyl chloride in question.

Should a primer be required, then apply a thin coat of PR-1543 to the tackified surface by brush and allow to dry 30 minutes at room temperature. If primed surfaces become contaminated before potting or molding, buff primed surface with a suitable abrasive and reapply a thin coat of PR-1543.

It should be noted that there are many formulations of polyvinyl chloride. Therefore, it is suggested that before production quantities of PR-1543 are ordered, tests be made to determine the adhesive strength of the PR-1543/PR-1592 system to the polyvinyl chloride in question.

NOTE: PR-1543 is hygroscopic and must be kept free of moisture. When PR-1543 hydrolyzes, a precipitate is formed decreasing the primer usefulness.

(d) Teflon* and Other Fluorocarbons
To obtain good adhesion to insulation made of Teflon and other fluorocarbon resins, it is essential that the insulation be etched or treated to provide a bondable surface. After neutralization of the etchant, in accordance with the manufacturer's instructions, apply PR-1592 directly to the etched surface without primer.

REPAIR
To obtain good adhesion to previously cured PR-1592, the surface should be buffed with a suitable abrasive to remove grease, oil, wax or mold release. Remove rubber particles with a dry, oil-free brush.

CAUTION: Do not use solvents for cleaning cured PR-1592. Apply new PR-1592 directly to buffed surface and cure as recommended. No primer is required.

Mixing Instructions

FOR TWO-PART UNITS

Do not open containers until ready to use.

Part A will solidify at room temperature. Prior to use, loosen lid and warm to 250° ± 10°F with thorough stirring. Do not heat over 260°F. When warming the material, use a thermometer to determine the actual material temperature. Liquefaction is complete when the material becomes smooth and uniform in appearance and loses all signs of graininess. Stirring is essential during liquefaction to provide a uniform material and to hasten melting. Care should be taken to dissolve all solidified Part A around the top of the container. Trace quantities of unliquefied Part A will cause premature solidification. Do not store Part A at temperatures exceeding 100°.

Premeasured quantities may be divided into smaller quantities by using the following proportions:
By weight 53 Parts A to 100 Parts B.

NOTE: After removing a portion of Part B from a full container, moisture in the air in the empty portion of the Part B container tends to cause the remaining material to skin over during extended periods of standing. This material may be used by removing the skin.

Where a dense compound free of voids is required, it is recommended that the mixed material be degassed before applications are made. Standard vacuum equipment may be used or, for small usages, the material may be degassed in a standard laboratory desiccator connected to a vacuum pump.

The following degassing procedure is recommended:
1. Stabilize Part A and Part B at 75° to 85°F before mixing.
2. Place Parts A and B in a clean, dry, metal container having at *least* twice the volume of the material to be degassed. Mix Part A and Part B thoroughly with a metal mixing paddle. NOTE: DO NOT USE WOOD.
3. When Parts A and B are mixed thoroughly, degas the mixture until foaming subsides which is approximately 10 minutes at a pressure of less than 5mm of mercury for a pint of material. Larger quantities will require slightly longer periods of degassing.
4. When the material is to be applied by extrusion gun, it is suggested that after tranferring the degassed material into the extrusion gun cartridge the material be degassed at a pressure of less than 5mm of mercury

*Registered trademark for DuPont tetrafluoroethylene resin.

for 2 minutes to remove any air which may have been entrapped during cartridge filling. If extra care is taken when filling cartridges with degassed material, such as flowing the material down the side of the cartridge, the material may not need to be degassed in the cartridge.

NOTE: After mixing Parts A and B, subsequent operations should be accomplished as quickly as possible to minimize the reduction of application life.

After units of PR-1592 have been mixed and degassed, they may be frozen for storage under refrigeration. Use of a quick-freeze technique is recommended so as to minimize the amount of application life that would be lost in a slower cooling procedure. One successful method is to immerse the filled cartridge in a slurry of dry ice and alcohol for 10 minutes. The temperature of the sealant will drop to approximately −70°F and the cartridges may be transferred to a refrigeration storage unit maintained at −20°F or below.

NOTE: Approximately 1 hour application life will be lost in the freezing and thawing process.

It is suggested that tests be conducted to determine whether degassing is necessary for the material to meet particular requirements. When it has been found that degassing is not necessary to meet requirements, mix entire contents of Part A with Part B, or use in the proportions as shown above, and thoroughly mix. Slow mixing by hand or with a mechanical mixer is recommended. A high-speed mechanical mixer will generate internal heat which reduces application life and will whip air into the mixture resulting in a porous material upon curing.

THAWING OF FROZEN CARTRIDGES

Frozen cartridges of PR-1592 must be thawed as follows:

NOTE: It is essential that the thawing time and temperature be controlled closely to obtain the maximum application life in the shortest thawing period. An increase in either thawing time or temperature will result in an incomplete thaw.

Remove cartridge from storage and thaw for 30 minutes in a 100° ± 5°F heating block or water bath. If an oven is used to thaw the material instead of the recommended water bath or heating block, the time and temperature will have to be determined because of the variations in oven controls and circulation.

NOTE: If a water bath is used, be sure water does not enter cartridge. The recommended method of preventing water from entering the cartridge is to use a metal sleeve, closed at one end, with a diameter just large enough to allow the cartridge to be inserted to the tip and then place the sleeve upright in the water bath.

CAUTION: When thawing frozen cartridges of PR-1592, keep cartridges in an upright position, nozzle end down with CaPlug in place, to prevent air that may have been drawn into the cartridge during freezing from entering and being trapped in the compound. After thawing is complete, just before placing the cartridge in the gun, insert a thin piece of metal or spatula blade between plunger and cartridge wall to the shoulder of plunger. Then force plunger down to exhaust any air between compound and plunger face and continue until material just starts to extrude between plunger and cartridge wall. Remove metal or spatula while holding plunger down.

Application Instructions

FOR POTTING

Application is accomplished by injecting the sealant into the end bell of the connector which has been coated previously with primer. Separate the wires evenly so that the potting compound will flow around all wires and soldered connections.

For most potting applications, a Semco #440 nozzle with 1/8" diameter has been found most practical. However, nozzles of smaller diameter are available.

When applying PR-1592 with an extrusion gun, the nozzle first should be inserted between the center wires so that the sealant will flow around the contacts. It may be necessary to reposition the nozzle for even coverage. Care should be taken to eliminate voids and air bubbles. It is good practice when filling the connector to keep the tip of the nozzle just above the swell of the material level, moving the nozzle up as the connector fills. The tip of the nozzle should not be held so as to allow it to become submerged nor should it be held so as to allow the material to fold.

In applying PR-1592, every effort should be made to eliminate voids and air bubbles. A small piece of metal, such as a welding rod, should be used to tamp or pack the compound around the wires and the base of the pins. In conjunction with the tamping, the connector should be tapped on a resilient surface or even mechanically vibrated to facilitate the flow of the sealant into the small recesses.

To reduce viscosity and enhance flow of compound, connectors or molds may be heated up to 140°F prior to filling. Do not heat the molding compound, as it will thicken and shorten application life.

Molds may be prepared to the exact shape and form required in a particular connector application by utilizing various plastic materials commercially available. A form or mold may be made for the back of a connector by using masking or polyethylene tape. Reference is made to the handbook, *Installation Practices for Aircraft Electric and Electronic Wiring*, (Navy) NAVAER 01-1A-505 or (USAF) T.O. 1-1A-14 dated 30 June 1975.

FOR MOLDING

When PR-1592 is used as a molding compound, molds should be provided for forming the particular form and shape required. To facilitate the removal of PR-1592 from the mold after curing, spread a thin film of mold release compound on mold surface to prevent adhesion. Metal molds may be coated with Teflon tetrafluoroethylene resin to provide a permanent release film and eliminate the necessity of using a mold release compound.

Inject PR-1592 into the mold, which has been coated previously with mold release and/or on previously prepared surfaces, and allow to firmly set before removing mold. It is recommended that injection holes be located in the bottom of the mold and air bleed holes located in the top of the mold to prevent air pockets in the mold. Flash may be trimmed with a sharp knife or razor blade.

Mold Release and Cure

The mold release time for PR-1592 is dependent upon the temperature, quantity of material, mold mass, ect. In molds containing less than 24 fluid ounces of PR-1592, the mold release time is approximately 2 hours at 180°F. In molds containing 24 to 48 fluid ounces of PR-1592, the mold release time is approximately 3 hours at 180°F. Longer times will be required for the mold release of PR-1592 in larger molds.

PR-1592 cures to a tough, resilient material having a 75 Shore A hardness in 6 hours at 180°F. PR-1592 will cure at 75°F, but the physical properties will be lower than when cured at 180°F.

Cleaning of Equipment

Wash equipment, tools and brushes with methyl ethyl ketone immediately after use or before material cures. Use commercial stripping compounds to remove cured material.

Safety Precautions

PR-420 contains flammable and volatile solvents. Keep away from heat, sparks and flame. Proper precautions for working with flammable liquids should be followed as well as applicable safety precautions.

Storage Life

Storage life of PR-1592 in two-part quantities is 12 months when stored at temperatures below 80°F in original unopened containers.

Storage life of premixed, frozen PR-1592 is at least 7 days when stored at −20°F or at least 30 days when stored at −40°F.

Storage life of PR-420 is approximately 1 year when stored in original unopened containers below 80°F.

Storage life of PR-1523-M and PR-1543 is approximately 6 months when stored in original unopened containers below 80°F.

NOTE: PR-1523-M and PR-1543 are hygroscopic and must be kept free of moisture. When these primers hydrolyze, a precipitate is formed decreasing the primers usefulness. Material containing precipitate should be tested to determine that primer is satisfactory before using.

Health Precautions

Part B of PR-1592 and related primers, PR-420, PR-1523-M, and PR-1543, contain isocyanates and can produce irritation or allergic reaction following contact with the skin, eyes or mucous membranes. Avoid all contact with the uncured components of these materials. In case of contact, promptly wash off with copious quantities of water and follow with a soap and water wash. Avoid breathing vapors. Use with adequate ventilation. Individuals with chronic respiratory problems or prior respiratory reactions to isocyanates should not be exposed to vapors.

PR-420 contains mixed solvents and a lead compound. Use adequate ventilation or air-supplied respirator during application.

In cases of extreme exposure or adverse reactions to any of the products mentioned above, remove affected personnel to fresh air and obtain immediate medical attention. If a rash develops, consult a physician. Ordinary hygienic principles such as washing hands before eating or smoking must be observed. For complete health and safety information, consult a Material Safety Data Sheet.

APPENDIX C. ENVIRONMENTAL CHAMBER SPECIFICATION SHEETS

TEMPERATURE/HUMIDITY CHAMBERS

ASSOCIATED ENVIRONMENTAL SYSTEMS

These are all standard units — readily available — many from stock. Now you can pick the unit to suit your needs and your budget . . . Bench Top and Floor Models — four temperature ranges to choose from — choice of 6 working volumes — 15 different units in all.

BENCH TOP MODELS—BHD Series

The BHD-403, 405 or 408 (last two digits indicate cubic foot working volume) are bench top units that will allow testing to meet known Mil. Std. Humidity Specifications. These units are basically Humidity chambers since they have a limited temperature range when compared to the Floor Models. In order to properly control humidity a refrigeration system is required.

Simple and easy to operate. The basic chambers have a digital dry bulb and a direct setting digital % RH controller (see optional extras for automatic programming and recording). Simply connect the power, 1/4" water supply line and 3/8" drain line and you are ready to operate.

Temperature Range: −18°C (0°F) to +93°C (+200°F)

Humidity Range: 20% to 95% ±5% RH within the range of +20°C (68°F) to +85°C (185°F) and is limited by a +4°C (39°F) dew point temperature, using standard controls. Optional microprocessor and recorders are available. Lower humidities available with optional chemical drier.

FLOOR MODELS—HD SERIES

This series of Humidity Chambers allows you to custom design a chamber to satisfy your needs and your budget. *Four working volumes* to choose from 08, 16, 33 and 64 Ft.³—*Three Temperature Ranges*.

Humidity Range: 20% to 95% RH within the range of +20°C (68°F) to +85°C (185°F) and is limited by a +4°C (39°F) dew point temperature.

With 86651 Programmable controller. Control stability of ±3% RH.

HOW TO ORDER BY MODEL NO.

Example: MODEL HD - 264 SC

- HD Series — Floor model
- 200 Series — (−70°C to +177°C)
- 64 cubic feet
- C = °C; F = °F
- S = standard voltage & frequency.
- O = optional non-standard power requirements

Select the temperature range:

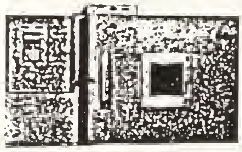
The 400 series has a temperature range of −18°C to +177°C (0°F to +350°F)
The 500 series has a temperature range of −40°C to +177°C (−40°F to +350°F)
The 200 series has a temperature range of −70°C to +177°C (−100°F to +350°F)

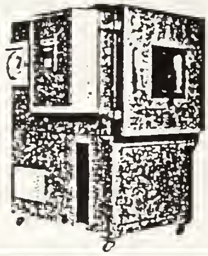
Select the working volume:

Indicate it as the last two digits of the model number – Sizes: 08, 16, 33 or 64 Ft.³.

FEATURES (illustrated on page 4)

- FAILSAFE– An adjustable high temperature failsafe is standard on all Associated Environmental System Chambers. It is factory set at the ultimate high temperature capability of the chamber. Upon receipt of the chamber, the customer should set the dry bulb controller to 10° above the highest test temperature and adjust the failsafe. This will prevent the test chamber from a temperature overrun.
- FUSIBLE LINKS (in the heater circuit) – For over temperature protection.
- MULTIPANE VIEWING WINDOWS – In the door of all chambers (optional on BHD Series).
- INTERNAL LIGHT – with external switch standard on all floor models optional on bench top units.
- PILOT LIGHTS – to monitor proper function of various systems.
- INTERIORS – All stainless steel type 304 heliarc welded.
- EXTERIORS – Heavy gauge, cold rolled steel with two coats of textured enamel finish.
- INSULATION — High density, low K factor, non-settling fiberglass.
- VAPOR GENERATORS – When humidity is required the controller signals the vapor generator to induce water vapor into the chamber. This method of creating high humidities is superior to the older methods of spraying water or passing warm air over water.
- VAPOR GENERATOR FAILSAFE – All A.E.S. humidity chambers are equipped with a factory set failsafe control to shut down the vapor generator in the event of a no water situation.
- FREEZE PROTECTION – Since all A.E.S. Chambers have the capability of going below the freezing point of water, each humidity chamber has a freeze protector which is factory set at 1.67°C (+35°F). This control actuates a solenoid valve to drain water from the chamber and prevent damage due to freezing of water.
- FORCED AIR CIRCULATION – High volume air circulation is standard on all units to achieve uniformity in the work space. The interior fan is connected to an external motor with a stainless steel shaft.
- WIRING – Coded readily accessible. In accordance with NEC.
- CONTROLS – All located in a hinged access panel with all relays and fuses readily accessible.
- ACCESS PORT – A 2" diameter access port and plug in left side wall on floor models and right side wall on bench tops is pre-punched in the metal – additional ports and plugs available.
- DIGITAL TEMPERATURE & HUMIDITY CONTROLLERS





BENCH TOP MODELS
BHD-403, 405, 408

FLOOR MODELS
HD-400, 500, 200

UNIT SPECIFICATIONS

		BENCH TOP MODELS Temp. Range: −18°C to +93°C Hum. Range: 20% to 95%			FLOOR MODELS Temp. Range: −18°C to +177°C Hum. Range: 20% to 95%				Temp. Range: −40°C to +177°C Hum. Range: 20% to 95%				Temp. Range: −73°C to +177°C Hum. Range: 20% to 95%			
MODEL NO.		BHD-403	BHD-405	BHD-408	HD-400 SERIES				HD-500 SERIES				HD-200 SERIES			
Working	Ft.³	03	05	08	08	16	33	64	08	16	33	64	08	16	33	64
Volume	Liters	85	142	227	227	453	765	1812	106 / 227	453	765	1812	227	453	765	1812
Power Required:	VAC*	115 / 100	115 / 100	230 / 200	230 / 200	230 / 230	230 / 230	230 / 230	230 / 230	230 / 200, 220	230 / 200, 220	230 / 200, 230	230 / 200, 220	230 / 200, 220	230 / 200, 220	230 / 380, 400
	Ø	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 1	1 / 3	3 / 3	3 / 3	1 / 3	3 / 3	3 / 3	3 / 3
	HZ	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50	60 / 50
	Amps	16 / 16	16 / 16	10 / 10	20 / 24	28 / 28	30 / 30	32 / 32	26 / 26	30 / 30	30 / 30	35 / 35	35 / 30	40 / 35	50 / 50	64 / 34
Shipping	Lbs.	400	528	600	650 750	900	1300	1800	750 / 850	1000	1400	1900	1050	1200	1725	2375
Weight:	Kg.	182	240	273	295 340	408	590	816	340 / 386	454	635	862	476	545	184	1080
Window in Door:	Inches	Optional	Optional	Optional	8x8	12 x 12	12 x 12	12 x 12	8 x 8	12 x 12	12 x 12	12 x 12	8 x 8	12 x 12	12 x 12	12 x 12
Access Port:		2" dia. (51 mm) port & plug center right side wall			2" dia. (51 mm) port & plug left side wall											
Nominal Heater	Kw	0.7	0.7	1.0	2.5	4.0	5.0	6.0	2.5	4.0	5.0	6.0	2.5	4.0	5.0	6.0
Refrigeration System:	HP	1/3	1/3	1/2	3/4	1	1	1½	1½	2	3	5	2 x 2	2 x 2	5 x 5	7½ x 7½
Temp. Rise Time • Ambient to Upper Limit in Min		30	30	40	40	40	60	30	40	40	60	30	40	40	60	30
Temp. Pull Down • Time: Ambient to Lower Limit in Min		45	45	45	60	60	60	60	60	60	60	60	90	60	120	120
Programmable Controller		Optional	Optional	Optional	#86651 PROGRAMMABLE CONTROLLER STANDARD											

•Rise & Pull Down Times may vary depending on ambient conditions and power supply

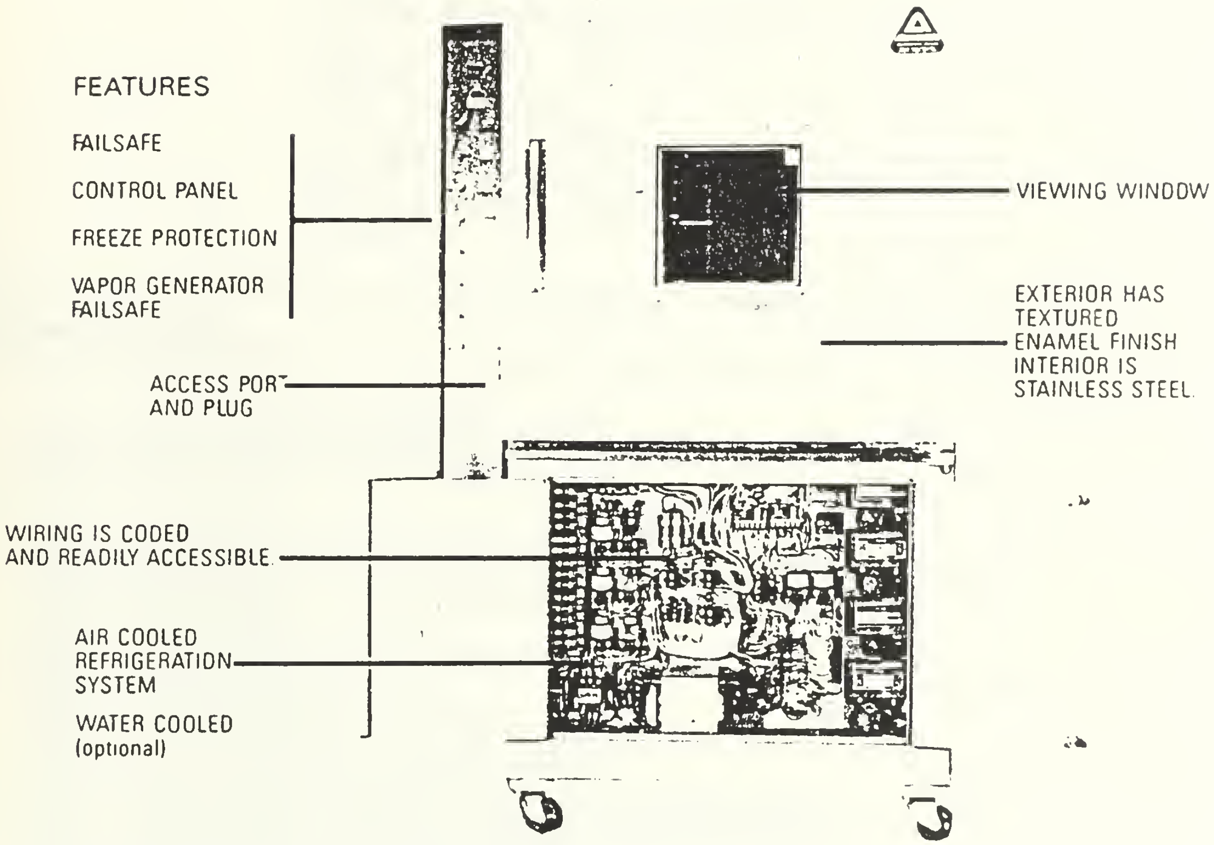
* 208 VAC requires additional transformer

	BHD-403	BHD-405	BHD-408	HD-400, 500, 200 SERIES			
Working Volume: Ft.³	03	05	08	08	16	33	64
Size: H x W x D In.	16 x 20 x 16	20 x 22 x 20	24 x 24 x 24	24 x 24 x 24	30 x 30 x 31	36 x 36 x 45	48 x 48 x 48
H x W x D cm.	41 x 51 x 41	51 x 56 x 51	61 x 61 x 61	61 x 61 x 61	76 x 76 x 79	92 x 92 x 114	122 x 122 x 122

utside: 32" H x 55" Wide x 36" depth (outside dimensions)

OPTIONAL EXTRAS

1. Programmable Controller 86651 (standard on all floor models)
2. 86649 IEEE-488 interface (required #1 option)
3. Product Protector limit controls
4. Honeywell 2 Pen 12" Circular Chart Recorder
5. 8" x 8" Window in Door for BHD-400 models
6. Manual Window Wiper
7. Internal Light with External Switch (standard on all floor models)
8. Water Storage Tank-External
9. Water Re-cycling System (includes external storage tank)
10. Water Demineralizer System
11. Extra Demineralizer Cartridge
12. Fully Adjustable Shelves
13. Additional Shelves
14. Casters
15. Additional Ports—Specify Location ¾", 2", 3", 4", 5", and 6" diameter
16. Chamber Cart (for BHD-403)
17. Floor Stand (BHD-405 & 408)
18. Liquid CO_2 Cooling Capability—specify psi
19. Liquid N2 Cooling Capability
20. Noise Reduction Package for floor models
21. Water Cooled Condenser
22. Other Power Source Requirements
23. Desiccant Dehumidifier for low % RH requirements (consult factory with specs)



	BHD-400 Series			HD-400, 500 or 200 Series			
	403	405	408	08	16	33	64
Dimensions:	**in/cm**	**in/cm**	**in/cm**	**in/cm**	**in/cm**	**in/cm**	**in/cm**
Outside Height	24/61	28/71	32/81	78/198	78/198	84/213	99/251
Outside Width	42/107	50/127	55/140	46/117	53/135	58/147	70/178
Outside Depth	24/61	30/76	36/91	52/132	60/152	72/183	80/203

APPENDIX D. RESONANCE TRACKING SYSTEM PROGRAM LISTING

```
10!   RT20C            : Resonance Tracking System
20!   Written by       : Brian Beaton
30!   Date             : 18 Mar 90
40!   Last modified    : 21 FEB 91
50!   Features added   : 1.Read one more DVM for Inphmag
60!                      BDAT change to 40 records
70!                      Measurement time 20 hours
80!                      Layout of printer output change
90!                      Format of data storage change(for Mac )
100!                     28 Jan 91 by Tan B.H.
110!                     2.Display In phase mag vs Time on CRT
120!                     Add plots of Inphmag vs Freq and
130!                     Inphmag vs Temp
140!                     13 Feb 91 by Tan B.H.
150!                     3.Compute reduced frequency
160!                     Convert old data of RT20B to RT20C format
170!                     BDAT change to 50 records
180!                     21 FEB 91
190!
200!******************************************************************
210! Program initialization
220!******************************************************************
230!
240      MASS STORAGE IS ":INTERNAL,4,0"
250      RE-STORE "RT20B:INTERNAL,4,1"
260!
270      OPTION BASE 0
280      DIM Thermistor(0:240),Resfreq(0:240),Time(0:240),Inphmag(0:240)
290      DIM Mod(0:240),X(0:240),Y(0:240),Alphat(0:240),Redfreq(0:240)
300      DIM Temp(0:240)
310      DIM Gtor(0:240),Elong(0:240),Eflex(0:240)
320      DIM Label$(0:25)[50]
330      DIM Main_title$[50],Sub_title$[50]
340      DIM X_axis_name$[50],Y_axis_name$[50]
350      DIM Block1$[50],Block2$[50],Block3$[50],Block4$[50]
360      DIM C1$[25],C2$[25],C3$[25],C4a$[25],C4b$[25],C5$[25]
370      DIM C6$[25],C7$[25],C8$[25],C9$[25],C10$[25]
380      DIM L1$[50],L2$[50],L3$[50],L4$[50]
390 !
400      Clear$=CHR$(255)&CHR$(75)              ! CLEAR SCRN key
410      Home$=CHR$(255)&CHR$(84)                    ! HOME key
420 !
430      Flag=0                 !Flag=1 to indicate editing data
440      Tmode=1                       ! first torsional mode
450      Lmode=1                     ! first longitudinal mode
460      Fmode=3.0112                     ! first flexural mode
470 !
480      Sample_rate=5               ! 1 sample every 5 minutes
490      Arg1=60/Sample_rate                ! samples per hour
500      Pi=PI                             ! 3.14159265
510      Default_grid$="Partial"           ! Full, Partial or No
```

```
520 !
530       Label$(1)="Resonance Frequency vs Time"      ! Graph Main Titles,
540       Label$(2)="Temperature was varied"       ! Sub Titles, Axes names
550       Label$(3)="Time, hours"
560       Label$(4)="Resonance frequency, Hz"
570       Label$(5)="Temperature, C"
580       Label$(6)="Resonance Frequency vs Temperature"
590       Label$(7)="Temperature vs Time"
600       Label$(8)="Frequency variation was observed"
610       Label$(9)="Young's Modulus vs Temperature"
620       Label$(10)="Shear Modulus vs Temperature"
630        Label$(11)="Shear modulus, Pa, x10^"
640        Label$(12)="Young's modulus, Pa, x10^"
650       Label$(13)="In Phase Magnitude, DCV"
660       Label$(14)="In Phase Mag vs Time"
670       Label$(15)="In Phase Mag vs Temp"
680       Label$(16)="In Phase Mag vs Freq"
690!
700       Pen1=1                        !  White     Default colors
710       Pen2=2                        !  Red
720       Pen3=3                        !  Yellow
730       Pen4=4                        !  Green
740       Pen5=5                        !  Cyan     (greenish blue)
750       Pen6=5                        !  Blue
760!
770!******************************************************************
780 Options:  ! Allow user to process existing data or collect new data
790!******************************************************************
800!
810       OUTPUT KBD;Clear$;                             ! Clear the CRT
820       OUTPUT KBD;Home$;                               ! Home display
830       STATUS 1,9;Screen                            ! Get screen width
840       Center=(Screen-28)/2              ! Leading spaces for centering
850       GCLEAR
860       PRINTER IS CRT                   ! Use CRT for displaying menu
870       PRINT TABXY(1,1)                  ! Start at top with blank line
880       PRINT TAB(Center);"Key       Purpose"
890       PRINT TAB(Center);"----------------------------"
900       PRINT TAB(Center);" 0    Process existing data"
910       PRINT TAB(Center);" 4    Collect new data"
920       PRINT TAB(Center);" 5    Editing existing data"
930       FOR Keynumber=0 TO 9                              ! Off all keys
940          ON KEY Keynumber LABEL "" GOSUB Comment1
950       NEXT Keynumber
960       ON KEY 0 LABEL "Existing Data" GOTO Existing_data  ! Turn on Key 0
970       ON KEY 4 LABEL "New Data" GOTO New_data           ! Turn on Key 4
980       ON KEY 5 LABEL "Editing Data" GOTO Editing_data    ! Turn on Key 5
990 Blink0:  WAIT 1
1000       DISP "Select an option"
1010       WAIT 1
1020       DISP
```

```
1030      GOTO Blink0
1040      RETURN
1050!********************************************************************
1060 New_data: ! Main program driver for collecting new data
1070!********************************************************************
1080      GOSUB Clear_keys
1090      GOSUB Init_param
1100      GOSUB Init_periph
1110      GOSUB Input_run_data
1120      GOSUB Create_new_file
1130!     GOSUB Draw_freq_time
1140      GOSUB Draw_mag_time
1150      GOSUB Take_plot_data
1160      GOSUB Close_file
1170      GOSUB Free_periph
1180      GOSUB Post_process
1190      STOP
1200!********************************************************************
1210 Existing_data: ! Main program driver for process existing data
1220!********************************************************************
1230      GOSUB Clear_keys
1240      GOSUB Open_old_file
1250      GOSUB Post_process
1260      STOP
1270!********************************************************************
1280 Editing_data: ! Main program driver to compute Redfreq for old data
1290!********************************************************************
1300      Flag=1
1310      GOSUB Clear_keys
1320      GOSUB Open_old_file
1330      GOSUB Calc_redfreq
1340      GOSUB Create_new_file
1350      GOSUB Close_file
1360      STOP
1370!********************************************************************
1380 Clear_keys: ! "Turns off" all softkeys and clears the screen
1390!********************************************************************
1400      FOR Keynumber=0 TO 9
1410         ON KEY Keynumber LABEL "" GOSUB Comment1
1420      NEXT Keynumber
1430      OUTPUT KBD;Clear$;
1440      RETURN
1450!********************************************************************
1460 Init_param: ! User sets the minimum and maximum values for initial plot
1470!********************************************************************
1480      Center=(Screen-46)/2           ! Leading spaces for centering
1490      PRINT TABXY(1,1)               ! Start at top with blank line
1500      PRINT TAB(Center);"Key     Purpose"
1510      PRINT TAB(Center);"----------------------------------------------"
1520      PRINT TAB(Center);" 0    Set minimum resonance frequency"
1530      PRINT TAB(Center);" 1    Set maximum resonance frequency"
```

```
1540      PRINT TAB(Center);" 2     Set minimum in phase magnitude"
1550      PRINT TAB(Center);" 3     Set maximum in phase magnitude"
1560      PRINT TAB(Center);" 5     Set minimum temperature in degrees, C"
1570      PRINT TAB(Center);" 6     Set maximum temperature in degress, C"
1580      PRINT TAB(Center);" 7     Set the default values"
1590      PRINT TAB(Center);" 8     Review the assigned values"
1600      PRINT TAB(Center);" 9     To proceed"
1610!
1620      ON KEY 0 LABEL "Min Freq, Hz" GOSUB Min_frequency
1630      ON KEY 1 LABEL "Max Freq, Hz" GOSUB Max_frequency
1640      ON KEY 2 LABEL "Min Mag, DCV" GOSUB Min_mag
1650      ON KEY 3 LABEL "Max Mag, DCV" GOSUB Max_mag
1660      ON KEY 4 LABEL "" GOSUB Comment1
1670      ON KEY 5 LABEL "Min Temp, C" GOSUB Min_temperature
1680      ON KEY 6 LABEL "Max Temp, C" GOSUB Max_temperature
1690      ON KEY 7 LABEL "Default Values" GOSUB Default_values
1700      ON KEY 8 LABEL "Review values" GOSUB Review_values
1710      ON KEY 9 LABEL "Proceed" GOTO Moveon
1720!
1730 Blink1: WAIT 1                          ! Wait for user selection and
1740         DISP "Select an option"           ! then take appropriate action
1750         WAIT 1
1760         DISP
1770         GOTO Blink1
1780 Moveon: GOSUB Clear_keys
1790            DISP "Proceeding ....."
1800          WAIT 1
1810           DISP
1820           RETURN
1830!*****************************************************************
1840 Comment1:  ! Alerts user when an unassigned soft key is selected
1850!*****************************************************************
1860       BEEP 300,.1
1870      DISP "This soft key is unassigned"
1880      WAIT 1
1890      DISP
1900      RETURN
1910!*****************************************************************
1920 Default_values:  ! Assigns default values for minimum and maximum T, F
1930!*****************************************************************
1940      User_freq_min=1650
1950      User_freq_max=1900
1960      User_temp_min=0
1970      User_temp_max=25
1980      DISP "The Default Values are Set"
1990      WAIT 1
2000      GOSUB Review_values
2010      RETURN
2020!*****************************************************************
2030 Min_frequency:  ! Accepts user input for minimum frequency
2040!*****************************************************************
```

```
2050        INPUT "The minimum frequency for the plot, in Hz ?",User_freq_min
2060        DISP "The minimum frequency is set at: ";User_freq_min;" Hz"
2070        WAIT 1
2080        DISP
2090        RETURN
2100!*************************************************************************
2110 Max_frequency:  ! Accepts user input for maximum frequency
2120!*************************************************************************
2130        INPUT "The maximum frequency for the plot, in Hz ?",User_freq_max
2140        DISP "The maximum frequency is set at: ";User_freq_max;" Hz"
2150        WAIT 1
2160        DISP
2170        RETURN
2180!*************************************************************************
2190 Min_mag:  ! Accepts user input for minimum magnitude
2200!*************************************************************************
2210        INPUT "The minimum magnitude for the plot, in DCV ?",User_mag_min
2220        DISP "The minimum magnitude is set at: ";User_mag_min
2230        WAIT 1
2240        DISP
2250        RETURN
2260!*************************************************************************
2270 Max_mag:  ! Accepts user input for maximum magnitude
2280!*************************************************************************
2290        INPUT "The maximum magnitude for the plot, in DCV ?",User_mag_max
2300        DISP "The maximum magnitude is set at: ";User_mag_max
2310        WAIT 1
2320        DISP
2330        RETURN
2340!*************************************************************************
2350 Review_values:  ! Presents currently assigned values for review
2360!*************************************************************************
2370        DISP "Minimum frequency: ";User_freq_min;" Hz"
2380        WAIT 1
2390        DISP " Maximum frequency: ";User_freq_max;" Hz"
2400        WAIT 1
2410        DISP "Minimum magnitude: ";User_mag_min;" DCV"
2420        WAIT 1
2430        DISP " Maximum magnitude: ";User_mag_max;" DCV"
2440        WAIT 1
2450        DISP "Minimum temperature: ";User_temp_min;" C"
2460        WAIT 1
2470        DISP " Maximum temperature: ";User_temp_max;" C"
2480        WAIT 1
2490        DISP
2500        RETURN
2510!*************************************************************************
2520 Min_temperature:  ! Accepts user input of minimum temperature
2530!*************************************************************************
2540        INPUT "Minimum temperature, degrees C ?",User_temp_min
2550        DISP "The minimum temperature is set at: ";User_temp_min;" C"
```

```
2560        WAIT 1
2570        DISP
2580        RETURN
2590!**************************************************************
2600 Max_temperature:  ! Accepts user input of maximum temperature
2610!**************************************************************
2620        INPUT "Maximum temperature, degrees C ?",User_temp_max
2630        DISP "The maximum temperature is set at: ";User_temp_max;" C"
2640        WAIT 1
2650        DISP
2660        RETURN
2670!**************************************************************
2680 Init_periph:  ! Initializes the voltmeter and the frequency counter
2690!**************************************************************
2700!       720 - HP5316A Universal Counter
2710!       722 - HP3456A Digital Voltmeter
2720!       724 - HP3478A Digital Multimeter (added on 23 Jan 91)
2730!
2740        OUTPUT 720;"IN"                           ! Default state
2750        OUTPUT 722;"HF4R1M66STG100STI"        ! 2 wire ohms, THMS degrees C
2760                                        ! 100 line cycles integration
2770        OUTPUT 724;"F1RAN5T1Z1D1"
2780        RETURN
2790!**************************************************************
2800 Free_periph:  ! Frees the voltmeter and the counter from the HPIB bus
2810!**************************************************************
2820        LOCAL 720
2830        LOCAL 722
2840        LOCAL 724
2850        RETURN
2860!**************************************************************
2870 Input_run_data:  ! Accepts user input of selected run data
2880!**************************************************************
2890        Center=(Screen-42)/2             ! Leading spaces for centering
2900        PRINT TABXY(1,1)                  ! Start at top with blank line
2910        PRINT TAB(Center);"Key        Purpose"
2920        PRINT TAB(Center);"------------------------------------------"
2930        PRINT TAB(Center);" 0      Enter rod identification"
2940        PRINT TAB(Center);" 1      Enter the run number for this mode"
2950        PRINT TAB(Center);" 2      Enter the mode for this run"
2960        PRINT TAB(Center);" 3      Enter the date for this run"
2970        PRINT TAB(Center);" 5      Enter the mass for this rod"
2980        PRINT TAB(Center);" 6      Enter the length for this rod"
2990        PRINT TAB(Center);" 7      Enter the diameter for this rod"
3000        PRINT TAB(Center);" 8      Review the information entered"
3010        PRINT TAB(Center);" 9      To proceed"
3020!
3030        ON KEY 0 LABEL "Rod ID" GOSUB Rod_id
3040        ON KEY 1 LABEL "Run No." GOSUB Run_number
3050        ON KEY 2 LABEL "Mode" GOSUB Mode
3060        ON KEY 3 LABEL "Date" GOSUB Date
```

```
3070     ON KEY 4 LABEL "" GOSUB Comment1
3080     ON KEY 5 LABEL "Rod Mass" GOSUB Rod_mass
3090     ON KEY 6 LABEL "Rod Length" GOSUB Rod_length
3100     ON KEY 7 LABEL "Rod Diameter" GOSUB Rod_diameter
3110     ON KEY 8 LABEL "Review entries" GOSUB Review_entrys
3120     ON KEY 9 LABEL "Proceed" GOTO Onward
3130 Blink2: WAIT 1
3140          DISP "Select an option or proceed"
3150          WAIT 1
3160          DISP
3170          GOTO Blink2
3180 Onward: Volume=(Length/100)*Pi*.25*(Diameter/100)^2
3190          Density=(Mass/1000)/Volume
3200          GOSUB Clear_keys
3210           DISP "Proceeding ..... "
3220          WAIT 1
3230          DISP
3240          RETURN
3250!******************************************************************
3260 Rod_id:  ! Accepts user input of rod identification
3270!******************************************************************
3280     INPUT "Rod identification block label (i.e. ECP4) ?",Block1$
3290     WHILE LEN(Block1$)>12
3300       DISP "Limit Rod Identification to 12 characters"
3310        BEEP 300,.1
3320       WAIT 1
3330       DISP
3340       INPUT "Rod identification block label (i.e. ECP4) ?",Block1$
3350     END WHILE
3360     DISP "The Rod ID is set at: ";Block1$
3370     WAIT 1
3380     DISP
3390     RETURN
3400!******************************************************************
3410 Run_number:  ! Accepts user input of run number
3420!******************************************************************
3430     INPUT "Run number for this mode (i.e. 4) ?",Block2$
3440     DISP "The Run number is set at: ";Block2$
3450     WAIT 1
3460     DISP
3470     RETURN
3480!******************************************************************
3490 Mode:  ! Accepts user input of the mode
3500!******************************************************************
3510     INPUT "Mode (i.e. Torsional, Longitudinal, Flexural) ?",Block3$
3520     SELECT UPC$(Block3$)
3530       CASE "FLEXURAL","TORSIONAL","LONGITUDINAL"
3540         DISP "The mode is set as:  ";Block3$
3550         WAIT 1
3560         DISP
3570       CASE ELSE
```

```
3580            BEEP 300,.1
3590            DISP "Choices are: Torsional, Longitudinal or Flexural"
3600            WAIT 1
3610            DISP
3620            GOTO Mode
3630        END SELECT
3640        RETURN
3650!******************************************************************
3660 Date:  ! Accepts user input of run date
3670!******************************************************************
3680        INPUT "The date for this sample (i.e. 10 SEP 89) ?",Block4$
3690        WHILE LEN(Block4$)>9
3700          DISP "Limit date entry to 9 characters"
3710          BEEP 300,.1
3720          WAIT 1
3730          DISP
3740          INPUT "The date for this sample (i.e. 10 SEP 89) ?",Block4$
3750        END WHILE
3760        DISP "The Date is set at: ";Block4$
3770        WAIT 1
3780        DISP
3790        RETURN
3800!******************************************************************
3810 Rod_mass:  ! Accepts user input of the rod mass
3820!******************************************************************
3830        INPUT "The mass for this rod (units: grams) ?",Mass
3840        DISP "The mass is set at: ";Mass;" grams"
3850        WAIT 1
3860        DISP
3870        RETURN
3880!******************************************************************
3890 Rod_length:  ! Accepts user input of the rod length
3900!******************************************************************
3910        INPUT "The length for this rod (units: centimeters) ?",Length
3920        DISP "The length is set at: ";Length;"centimeters"
3930        WAIT 1
3940        DISP
3950        RETURN
3960!******************************************************************
3970 Rod_diameter:  ! Accepts user input of the rod diameter
3980!******************************************************************
3990        INPUT "The diameter for this rod (units: centimeters) ?",Diameter
4000        DISP "The diameter is set at: ";Diameter;" centimeters"
4010        WAIT 1
4020        DISP
4030        RETURN
4040!******************************************************************
4050 Review_entrys:  ! Presents currently assigned values for review
4060!******************************************************************
4070        DISP "Rod ID: ";Block1$
4080        WAIT 1
```

```
4090       DISP " Run: ";Block2$
4100       WAIT 1
4110       DISP "Mode: ";Block3$
4120       WAIT 1
4130       DISP " Date: ";Block4$
4140       WAIT 1
4150       DISP "Mass: ";Mass;"grams"
4160       WAIT 1
4170       DISP " Length: ";Length;" centimeters"
4180       WAIT 1
4190       DISP "Diameter: ";Diameter;" centimeters"
4200       WAIT 1
4210       DISP
4220       RETURN
4230!******************************************************************
4240 Draw_mag_time:  ! Produces Magnitude vs Time graph w/o curve
4250!******************************************************************
4260       Main_title$=Label$(14)
4270       Sub_title$=Label$(2)
4280       X_axis_name$=Label$(3)
4290       Y_axis_name$=Label$(13)
4300       Xmin=0
4310       Xmax=20
4320       Ymin=Actual_mag_min
4330       Ymax=Actual_mag_max
4340       GOSUB Generic_plot
4350       RETURN
4360!******************************************************************
4370 Draw_freq_time:  ! Produces Frequency vs Time graph w/o curve
4380!******************************************************************
4390       Main_title$=Label$(1)
4400       Sub_title$=Label$(2)
4410       X_axis_name$=Label$(3)
4420       Y_axis_name$=Label$(4)
4430       Xmin=0
4440       Xmax=20
4450       Ymin=Actual_freq_min              ! Actual minimum frequency
4460       Ymax=Actual_freq_max              ! Actual maximum frequency
4470       GOSUB Generic_plot
4480       RETURN
4490!******************************************************************
4500 Young_mod: ! Compute Young's modulus in flexure modes
4510!******************************************************************
4520       D=Diameter/100
4530       L=Length/100
4540       Arg6=Density*((32*L^2)/(Pi*D*Fmode^2))^2
4550       Eflex(I)=Arg6*Resfreq(I)^2
4560       RETURN
4570!******************************************************************
4580 Shear_mod: ! Compute Shear Modulus
4590!******************************************************************
```

```
4600       D=Diameter/100
4610       L=Length/100
4620       Arg5=(Density*4*L^2)/(Tmode^2)
4630       Gtor(J)=(Arg5*Resfreq(J)^2)
4640       RETURN
4650!***********************************************************************
4660 Lyoung_mod: ! Compute Young's modulus in longitudinal mode
4670!***********************************************************************
4680       D=Diameter/100
4690       L=Length/100
4700       Arg7=(Density*4*L^2)/(Lmode^2)
4710       Elong(K)=Arg7*Resfreq(K)^2
4720       RETURN
4730!***********************************************************************
4740 Compute_redfreq: ! Compute redfreq of new data
4750!***********************************************************************
4760       Temp(I)=Thermistor(I)+273.15
4770!       X(I)=-12.9*(Temp(I)-283.15)/(107+Temp(I)-283.15) ! PR 1592 only
4780       X(I)=-21.5*(Temp(I)-211)/(43.1+Temp(I)-211) ! Plexi-glass only
4790       Y(I)=X(I)*LOG(10)
4800       Alphat(I)=EXP(Y(I))
4810       Redfreq(I)=Resfreq(I)*Alphat(I)
4820       RETURN
4830!***********************************************************************
4840 Calc_redfreq: ! Convert RT20B to RT20C format
4850!***********************************************************************
4860       FOR I=0 TO 20*Arg1
4870          Temp(I)=Thermistor(I)+273.15
4880          X(I)=-12.9*(Temp(I)-283.15)/(107+Temp(I)-283.15) !PR 1592 only
4890          Y(I)=X(I)*LOG(10)
4900          Alphat(I)=EXP(Y(I))
4910          Redfreq(I)=Resfreq(I)*Alphat(I)
4920        NEXT I
4930        RETURN
4940!***********************************************************************
4950 Compute_modulus:  ! Computes appropriate material modulus based on mode
4960!***********************************************************************
4970        DISP "Computing appropriate modulus ........"
4980       D=Diameter/100                          ! convert to meters
4990       L=Length/100                            ! convert to meters
5000       SELECT UPC$(Block3$)
5010         CASE "FLEXURAL"
5020           Arg2=Density*((32*L^2)/(Pi*D*Fmode^2))^2
5030           Eflex_max=Arg2*Actual_freq_max^2
5040           Power=LOG(Eflex_max) DIV LOG(10)
5050           Scale_factor=10^Power
5060           Scale_eflex_max=Eflex_max/Scale_factor
5070           Scale_eflex_min=(Arg2*Actual_freq_min^2)/Scale_factor
5080           FOR I=0 TO 20*Arg1
5090              Eflex(I)=(Arg2*Resfreq(I)^2)/Scale_factor
5100           NEXT I
```

```
5110        CASE "TORSIONAL"
5120          Arg3=(Density*4*L^2)/(Tmode^2)
5130          Gtor_max=Arg3*Actual_freq_max^2
5140          Power=LOG(Gtor_max) DIV LOG(10)
5150          Scale_factor=10^Power
5160          Scale_gtor_max=Gtor_max/Scale_factor
5170          Scale_gtor_min=(Arg3*Actual_freq_min^2)/Scale_factor
5180          FOR J=0 TO 20*Arg1
5190             Gtor(J)=(Arg3*Resfreq(J)^2)/Scale_factor
5200          NEXT J
5210        CASE "LONGITUDINAL"
5220          Arg4=(Density*4*L^2)/(Lmode^2)
5230          Elong_max=Arg4*Actual_freq_max^2
5240          Power=LOG(Elong_max) DIV LOG(10)
5250          Scale_factor=10^Power
5260          Scale_elong_max=Elong_max/Scale_factor
5270          Scale_elong_min=(Arg4*Actual_freq_min^2)/Scale_factor
5280          FOR K=O TO 20*Arg1
5290             Elong(K)=(Arg4*Resfreq(K)^2)/Scale_factor
5300          NEXT K
5310      END SELECT
5320      DISP
5330      RETURN
5340!*******************************************************************
5350 Percent_moduli:  ! Determines the percent change in modulus per degree C
5360!*******************************************************************
5370      Delta_temp=Actual_temp_max-Actual_temp_min
5380      Fsum2pt=Actual_freq_max+Actual_freq_min
5390      Fdiff2pt=Actual_freq_max-Actual_freq_min
5400      Fminls=Actual_temp_max*Slope+Intercept
5410      Fmaxls=Actual_temp_min*Slope+Intercept
5420      Fsumls=Fmaxls+Fminls
5430      Fdiffls=Fmaxls-Fminls
5440      Prcnt_per_c_2pt=100*4*(Fdiff2pt/Fsum2pt)/Delta_temp     ! 2 point
5450      Prcnt_per_c_ls=100*4*(Fdiffls/Fsumls)/Delta_temp   ! least squares
5460      RETURN
5470!*******************************************************************
5480 Mag_temp:  ! Produces In phase mag vs Temperature graph w/ curve
5490!*******************************************************************
5500      Main_title$=Label$(15)
5510      Sub_title$=Label$(2)
5520      X_axis_name$=Label$(5)
5530      Y_axis_name$=Label$(13)
5540      Xmin=Actual_temp_min
5550      Xmax=Actual_temp_max
5560      Ymin=Actual_mag_min
5570      Ymax=Actual_mag_max
5580      GOSUB Generic_plot
5590      CALL Generic_curve(Pen3,Thermistor(*),Inphmag(*),20*Arg1)
5600      RETURN
```

```
5610!************************************************************
5620 Mag_freq:   !Produces In phase mag vs Resonant frequencies
5630!************************************************************
5640       Main_title$=Label$(16)
5650       Sub_title$=" "
5660       X_axis_name$=Label$(4)
5670       Y_axis_name$=Label$(13)
5680       Xmin=Actual_freq_min
5690       Xmax=Actual_freq_max
5700       Ymin=Actual_mag_min
5710       Ymax=Actual_mag_max
5720       GOSUB Generic_plot
5730       CALL Generic_curve(Pen3,Resfreq(*),Inphmag(*),20*Arg1)
5740       RETURN
5750!************************************************************
5760 Shear_temp:  ! Produces Shear modulus vs Temperature graph w/ curve
5770!************************************************************
5780       Main_title$=Label$(10)
5790       Sub_title$=" "
5800       X_axis_name$=Label$(5)
5810       Y_axis_name$=Label$(11)&VAL$(Power)
5820       Xmin=Actual_temp_min                ! Actual minimum temperature
5830       Xmax=Actual_temp_max                ! Actual maximum temperature
5840       Ymin=Scale_gtor_min               ! Scaled minimum shear modulus
5850       Ymax=Scale_gtor_max               ! Scaled maximum shear modulus
5860       GOSUB Generic_plot
5870       CALL Generic_curve(Pen3,Thermistor(*),Gtor(*),20*Arg1)
5880       RETURN
5890!************************************************************
5900 Young_temp:  ! Produces Young's modulus vs Temperature graph w/ curve
5910!************************************************************
5920       Main_title$=Label$(9)
5930       Sub_title$=" "
5940       X_axis_name$=Label$(5)
5950       Y_axis_name$=Label$(12)&VAL$(Power)
5960       Xmin=Actual_temp_min                ! Actual minimum temperature
5970       Xmax=Actual_temp_max                ! Actual maximum temperature
5980       SELECT UPC$(Block3$)
5990         CASE "FLEXURAL"
6000           Ymin=Scale_eflex_min          ! Scaled minimum Y (flexural)
6010           Ymax=Scale_eflex_max          ! Scaled maximum Y (flexural)
6020           GOSUB Generic_plot
6030           CALL Generic_curve(Pen3,Thermistor(*),Eflex(*),20*Arg1)
6040         CASE "LONGITUDINAL"
6050           Ymin=Scale_elong_min       ! Scaled minimum Y (longitudinal)
6060           Ymax=Scale_elong_max       ! Scaled maximum Y (longitudinal)
6070           GOSUB Generic_plot
6080           CALL Generic_curve(Pen3,Thermistor(*),Elong(*),20*Arg1)
6090       END SELECT
6100       RETURN
```

```
6110!*****************************************************************
6120 Generic_plot:  ! Produces design and layout of line graph
6130!*****************************************************************
6140      GINIT                    ! Initialize various graphics parameters
6150      GCLEAR                          ! Clear the graphics display
6160      GRAPHICS ON                      ! Turn the graphics display on
6170      OUTPUT KBD;Clear$;                         ! Clear the CRT
6180!
6190      IF Plot_device$="Plotter" THEN   ! Route output to HP7475A plotter
6200         GRAPHICS OFF
6210         BEEP 1000,.1
6220         DISP "Press CONTINUE when the plotter is ready"
6230         PAUSE
6240         OUTPUT 705;"IP 1300,1000,9000,6750;"     ! Sets scaling points
6250         PLOTTER IS 705,"HPGL"
6260      END IF
6270!
6280      Xgdumax=100*MAX(1,RATIO)          ! How many gdu's wide screen is
6290      Ygdumax=100*MAX(1,1/RATIO)        ! How many gdu's high screen is
6300       CALL Scale(.02,.98,.10,.98,Top,Left,Xcntr,Ycntr,Xgdumax,Ygdumax)
6310      PEN Pen2
6320      FRAME
6330!
6340      IF LEN(Main_title$)>30 THEN                  ! Size main title
6350         CALL Label(4,.6,0,6,Pen2,Xcntr,Top-2,Main_title$)
6360      ELSE
6370         CALL Label(6,.6,0,6,Pen2,Xcntr,Top-2,Main_title$)
6380      END IF
6390!
6400       CALL Label(4,.6,0,6,Pen2,Xcntr,.9*Top,Sub_title$)
6410      CALL Block_info(Block1$,Block2$,Block3$,Block4$,Xgdumax,Pen5,Pen2)
6420       CALL Scale(.15,.90,.25,.8,Top,Left,Xcntr,Ycntr,Xgdumax,Ygdumax)
6430      CLIP OFF
6440       CALL Label(4,.6,0,4,Pen5,Xcntr,-18,X_axis_name$)
6450       CALL Label(4,.6,90,4,Pen5,-12,Ycntr,Y_axis_name$)
6460      CLIP ON
6470!
6480      SELECT Xscale$
6490        CASE "Auto scale X"                ! Auto scale X axis
6500          CALL Xscale(Xmin,Xmax,Xminor,Xmajor)
6510        CASE "User scale X"                ! User scale X axis
6520          SELECT Pass$
6530            CASE "Initial"                 ! Initial pass
6540              Xmin=0                  ! Minimum time, hours
6550              Xmax=20                  ! Maximum time, hours
6560              Xmajor=1
6570              Xminor=.5
6580            CASE "Follow on"          ! Use user modified values
6590              Xmin=Xmin_manual
6600              Xmax=Xmax_manual
6610              Xmajor=Xmajor_manual
```

```
6620              Xminor=Xminor_manual
6630           END SELECT
6640        END SELECT
6650!
6660        SELECT Yscale$
6670          CASE "Auto scale Y"                    ! Auto scale Y axis
6680            CALL Yscale(Ymin,Ymax,Yminor,Ymajor)
6690          CASE "User scale Y"                    ! User scale Y axis
6700             SELECT Pass$
6710               CASE "Initial"                    ! Initial pass
6720!                 Ymin=User_freq_min       ! Use user entered min freq
6730!                 Ymax=User_freq_max    ! Use user entered maximum freq
6740                  Ymin=User_mag_min     ! Use user entered min mag
6750                  Ymax=User_mag_max     ! Use user entered max mag
6760                  Ymajor=(Ymax-Ymin)/5
6770                  Yminor=Ymajor/5
6780                  Pass$="Follow on"
6790                  Xscale$="Auto scale X"
6800                  Yscale$="Auto scale Y"
6810               CASE "Follow on"            ! Use user modified values
6820                  Ymin=Ymin_manual
6830                  Ymax=Ymax_manual
6840                  Ymajor=Ymajor_manual
6850                  Yminor=Yminor_manual
6860           END SELECT
6870        END SELECT
6880        WINDOW Xmin,Xmax,Ymin,Ymax
6890!
6900        CALL Lbl_axes(2,.6,Pen4,Xmin,Xmax,Xmajor,Ymin,Ymax,Ymajor) ! Axes
6910        PEN Pen2
6920        AXES Xminor,Yminor,Xmin,Ymin,Xmajor/Xminor,Ymajor/Yminor,3
6930        AXES Xminor,Yminor,Xmax,Ymax,Xmajor/Xminor,Ymajor/Yminor,3
6940!
6950        SELECT Grid_type$                                  ! Grid
6960          CASE "Partial"
6970            GRID Xmajor,Ymajor,Xmin,Ymin
6980          CASE "Full"
6990            GRID Xminor,Yminor,Xmin,Ymin,Xmajor/Xminor,Ymajor/Yminor,1
7000        END SELECT
7010!
7020        PENUP
7030        GRAPHICS ON
7040        RETURN
7050!*****************************************************************
7060 Take_plot_data:  ! Collects frequency vs temperature data during the run
7070!*****************************************************************
7080        ON KEY 0 LABEL "Take Data" GOTO Take
7090        FOR Keynumber=1 TO 9
7100          ON KEY Keynumber LABEL "" GOSUB Comment1
7110        NEXT Keynumber
7120 Wait:   GOTO Wait
```

```
7130 Take:  ON KEY 0 LABEL "" GOSUB Comment1
7140        PEN Pen3
7150        OUTPUT KBD;"Taking data .....";
7160        T0=TIMEDATE
7170        SELECT UPC$(Block3$)
7180          CASE "FLEXURAL"
7190            FOR I=0 TO 20*Arg1
7200              ENTER 720;Resfreq(I)
7210              ENTER 722;Thermistor(I)
7220              ENTER 724;Inphmag(I)
7230              Time(I)=I/Arg1
7240              PLOT Time(I),Inphmag(I)
7250              GOSUB Compute_redfreq
7260              GOSUB Young_mod
7270              OUTPUT @Path_1;Eflex(I),Thermistor(I),Resfreq(I),Inphmag
(I),Redfreq(I)
7280              DISP I
7290              WAIT 295.787   !Adjustment for 1 sample every 5 minutes
7300            NEXT I
7310          CASE "TORSIONAL"
7320            FOR J=0 TO 20*Arg1
7330              ENTER 720;Resfreq(J)
7340              ENTER 722;Thermistor(J)
7350              ENTER 724;Inphmag(J)
7360              Time(J)=J/Arg1
7370              PLOT Time(J),Inphmag(J)
7380              GOSUB Compute_redfreq
7390              GOSUB Shear_mod
7400              OUTPUT @Path_1;Gtor(J),Thermistor(J),Resfreq(J),Inphmag(J
),Redfreq(J)
7410              DISP J
7420              WAIT 295.787
7430            NEXT J
7440          CASE "LONGITUDINAL"
7450            FOR K=0 TO 20*Arg1
7460              ENTER 720;Resfreq(K)
7470              ENTER 722;Thermistor(K)
7480              ENTER 724;Inphmag(K)
7490              Time(K)=K/Arg1
7500              PLOT Time(K),Inphmag(K)
7510              GOSUB Compute_redfreq
7520              GOSUB Lyoung_mod
7530              OUTPUT @Path_1;Elong(K),Thermistor(K),Resfreq(K),Inphmag(
K),Redfreq(K)
7540              DISP K
7550              WAIT 295.787
7560            NEXT K
7570        END SELECT
7580        T1=TIMEDATE
7590        DISP "IT TOOK ";DROUND(T1-T0,4);"SECONDS"
7600        WAIT 10
```

```
7610      OUTPUT KBD;Clear$;                          ! Clears the CRT
7620      BEEP
7630      ON KEY 0 LABEL "Post Process" GOTO 7650
7640 Wait1:  GOTO Wait1
7650      RETURN
7660!******************************************************************
7670 Post_process:  ! Permits user to extract plots, tables, and other info
7680!******************************************************************
7690      GCLEAR
7700       CALL Least_squares(20*Arg1,Thermistor(*),Resfreq(*),A,B,C,D,E,F,G)
7710      Slope=A          ! Keeps call to Least_squares to one program line
7720      Intercept=B
7730      Correlation=C
7740      Slope_error=D
7750      Intrcpterr=E
7760      Tmean=F
7770      Fmean=G
7780!
7790      Actual_temp_min=MIN(Thermistor(*))     ! Find maximum and minimum
7800      Actual_temp_max=MAX(Thermistor(*))    ! temperature and frequency
7810      Actual_freq_min=MIN(Resfreq(*))
7820      Actual_freq_max=MAX(Resfreq(*))
7830      Actual_mag_min=MIN(Inphmag(*))
7840      Actual_mag_max=MAX(Inphmag(*))
7850!
7860      Volume=.25*(Length/100)*Pi*(Diameter/100)^2
7870      GOSUB Percent_moduli
7880      GOSUB Compute_modulus
7890!
7900      OUTPUT KBD;Clear$;                          ! Clear the CRT
7910      OUTPUT KBD;Home$;                             ! Home display
7920      GCLEAR
7930      PRINT TABXY(1,1)                ! Start at top with bleank line
7940      Center=(Screen-42)/2            ! Leading spaces for centering
7950      PRINT TAB(Center);"Key            Purpose"
7960      PRINT TAB(Center);"------------------------------------------"
7970      PRINT TAB(Center);" 0   Plot Frequency vs Time"
7980      PRINT TAB(Center);" 1   Plot Temperature vs Time"
7990      PRINT TAB(Center);" 2   Plot Frequency vs Temperature"
8000      SELECT UPC$(Block3$)
8010        CASE ="TORSIONAL"
8020          PRINT TAB(Center);" 3   Plot Shear modulus vs Temperature"
8030        CASE ="FLEXURAL"
8040          PRINT TAB(Center);" 3   Plot Young's modulus vs Temperature"
8050        CASE ="LONGITUDINAL"
8060          PRINT TAB(Center);" 3   Plot Young's modulus vs Temperature"
8070      END SELECT
8080      PRINT TAB(Center);" 4   Send Information to the Printer"
8090      PRINT TAB(Center);" 5   Select the graph output device"
8100      PRINT TAB(Center);" 6   Plot In phase mag vs Temperature"
8110      PRINT TAB(Center);" 7   Plot In phase mag vs Temperature"
```

```
8120      PRINT TAB(Center);" 7   Select the type of X axis scaling"
8130      PRINT TAB(Center);" 8   Select the type of Y axis scaling"
8140      PRINT TAB(Center);" 9   Exit this program"
8150!
8160      ON KEY 0 LABEL "Freq vs Time" GOSUB Freq_time
8170      ON KEY 1 LABEL "Temp vs Time" GOSUB Temp_time
8180      ON KEY 2 LABEL "Freq vs Temp" GOSUB Freq_temp
8190      SELECT UPC$(Block3$)
8200        CASE ="TORSIONAL"
8210          ON KEY 3 LABEL "G vs Temp" GOSUB Shear_temp
8220        CASE ="FLEXURAL"
8230          ON KEY 3 LABEL "E vs Temp" GOSUB Young_temp
8240        CASE ="LONGITUDINAL"
8250          ON KEY 3 LABEL "E vs Temp" GOSUB Young_temp
8260        CASE ELSE
8270          ON KEY 3 LABEL "" GOSUB Comment1
8280      END SELECT
8290      ON KEY 4 LABEL "Print Info" GOSUB Dump_info
8300      ON KEY 5 LABEL "Output Device" GOSUB Output_device
8310!     ON KEY 6 LABEL "Grid Option" GOSUB Grid_option
8320      ON KEY 6 LABEL "Imag vs Temp" GOSUB Mag_temp
8330!     ON KEY 7 LABEL "X scale option" GOSUB Xscale_option
8340      ON KEY 7 LABEL "Imag vs Freq" GOSUB Mag_freq
8350      ON KEY 8 LABEL "Y scale option" GOSUB Yscale_option
8360      ON KEY 9 LABEL "Exit Program" GOSUB Program_end
8370!
8380 Blink3: WAIT 1
8390      DISP "Make a DECISION"
8400      WAIT 1
8410      DISP
8420      GOTO Blink3
8430      RETURN
8440!******************************************************************
8450 Grid_option:  ! Accepts the user's choice for the plot grid
8460!******************************************************************
8470      GRAPHICS OFF                    ! Turns off graphics display
8480      OUTPUT KBD;Clear$;                         ! Clears the CRT
8490      DISP Grid_type$;" grid is currently selected"
8500      INPUT "Enter F - full; P - partial; N - No grid ?",Response$
8510      SELECT Response$
8520        CASE "F"
8530          Grid_type$="Full"
8540        CASE "P"
8550          Grid_type$="Partial"
8560        CASE "N"
8570          Grid_type$="No"
8580        CASE ELSE
8590          DISP "No change"
8600          WAIT 1
8610          DISP
8620          WAIT 1
```

```
8630      END SELECT
8640      DISP Grid_type$;" grid is selected"
8650      WAIT 1
8660      DISP
8670      RETURN
8680!*****************************************************************
8690 Dump_info:  ! Sends selected data and table information to the printer
8700!*****************************************************************
8710      PRINTER IS 701
8720      Perfskip$=CHR$(27)&CHR$(38)&CHR$(108)&CHR$(49)&CHR$(76)
8730      Formfeed$=CHR$(12)
8740      PRINT Perfskip$                    ! Skip on Perforation
8750      PRINT Formfeed$
8760      PRINT USING "3/,#"                    ! Three line feeds
8770      PRINT "Rod:    "&Block1$;TAB(70);"Page 1 of 2"
8780      PRINT "Run:    "&Block2$
8790      PRINT "Mode:   "&Block3$
8800      PRINT "Date:   "&Block4$
8810      PRINT USING "3/,#"                  ! Three more line feeds
8820!
8830      C1$="Time"
8840      C2$="Temperature"
8850      C3$="Frequency"
8860      C4a$="Shear modulus"
8870      C4b$="Young's modulus"
8880      C5$="In Phase Component"
8890      C6$="hours"
8900      C7$="deg C"
8910      C8$="Hz"
8920      C9$="Pa*10^"
8930      C10$="DCV"
8940!
8950      SELECT UPC$(Block3$)
8960        CASE "TORSIONAL"
8970          PRINT USING 8980;C1$,C2$,C3$,C4a$,C5$
8980          IMAGE 4A,6X,11A,5X,9A,5X,13A,5X,18A
8990          PRINT
9000          PRINT USING 9010;C6$,C7$,C8$,C9$,Power,C10$
9010          IMAGE 5A,8X,5A,11X,2A,12X,6A,ZZ,14X,3A,12X
9020          PRINT
9030          FOR I=0 TO 20*Arg1 STEP Arg1
9040          PRINT USING 9050;Time(I),Thermistor(I),Resfreq(I),Gtor(I),In
phmag(I)
9050                                    IMAGE    X,3D,8X,SDD.DDD,4X,
DDDD.DDDE,9X,D.DDD,13X,SDD.DDDDDE
9060          NEXT I
9070        CASE "FLEXURAL"
9080          PRINT USING 9140;C1$,C2$,C3$,C4b$,C5$
9090          PRINT
9100          PRINT USING 9010;C6$,C7$,C8$,C9$,Power,C10$
9110          PRINT
```

```
9120        FOR J=0 TO 20*Arg1 STEP Arg1
9130          PRINT USING 9050;Time(J),Thermistor(J),Resfreq(J),Eflex(J)
,Inphmag(I)
9140          IMAGE 4A,6X,11A,5X,9A,5X,15A,3X,18A
9150        NEXT J
9160      CASE "LONGITUDINAL"
9170         PRINT USING 9140;C1$,C2$,C3$,C4b$,C5$
9180        PRINT
9190         PRINT USING 9010;C6$,C7$,C8$,C9$,Power,C10$
9200        PRINT
9210        FOR K=0 TO 20*Arg1 STEP Arg1
9220          PRINT USING 9050;Time(K),Thermistor(K),Resfreq(K),Elong(K)
,Inphmag(I)
9230        NEXT K
9240      END SELECT
9250!
9260      PRINT Formfeed$                ! Advance to top of next page
9270      PRINT USING "3/,#"                  ! Three more line feeds
9280      PRINT "Rod:    "&Block1$;TAB(70);"Page 2 of 2"
9290      PRINT "Run:    "&Block2$
9300      PRINT "Mode:   "&Block3$
9310      PRINT "Date:   "&Block4$
9320!
9330      PRINT USING "3/,#"                  ! Three more line feeds
9340      PRINT "Physical properties:"
9350      PRINT
9360      PRINT USING "3X,12A,14X,DDD.DDD";"Mass, grams:",Mass
9370      PRINT USING "3X,20A,06X,DDD.DDD";"Length, centimeters:",Length
9380      PRINT USING "3X,22A,04X,DDD.DDD";"Diameter, centimeters:",Diameter
9390      PRINT USING "3X,21A,07X,D.DDDE";"Volume, cubic meters:",Volume
9400      PRINT USING "3X,16A,09X,DDDD.D";"Density, kg/m^3:",Density
9410!
9420      PRINT USING "3/,#"                  ! Three more line feeds
9430      PRINT "Least-squares fit results [frequency versus temperature]:"
9440      PRINT
9450      PRINT USING "3X,12A,13X,DDDD.DDD";"Slope, Hz/C:",Slope
9460      PRINT USING "3X,18A,07X,DDDD.DDD";"Slope error, Hz/C:",Slope_error
9470      PRINT USING "3X,14A,11X,DDDD.DDD";"Intercept, Hz:",Intercept
9480      PRINT USING "3X,20A,05X,DDDD.DDD";"Intercept error, Hz:",Intrcpterr
9490      PRINT USING "3X,12A,13X,DDDD.DDDDD";"Correlation:",Correlation
9500      PRINT USING "3X,20A,05X,DDDD.DDD";"Mean temperature, C:",Tmean
9510      PRINT USING "3X,19A,06X,DDDD.DDD";"Mean frequency, Hz:",Fmean
9520      PRINT
9530      PRINT
9540      PRINT "Other statistics:"
9550      PRINT
9560      Tmin=Actual_temp_min
9570      Tmax=Actual_temp_max
9580      Tave=(Tmax+Tmin)/2
9590      Fmin=Actual_freq_min
9600      Fmax=Actual_freq_max
```

```
9610     Fave=(Fmax+Fmin)/2
9620     PRINT USING "3X,23A,02X,DDDD.DDD";"Minimum temperature, C:",Tmin
9630     PRINT USING "3X,23A,02X,DDDD.DDD";"Average temperature, C:",Tave
9640     PRINT USING "3X,23A,02X,DDDD.DDD";"Maximum temperature, C:",Tmax
9650     PRINT
9660     PRINT USING "3X,22A,03X,DDDD.DDD";"Minimum frequency, Hz:",Fmin
9670     PRINT USING "3X,22A,03X,DDDD.DDD";"Average frequency, Hz:",Fave
9680     PRINT USING "3X,22A,03X,DDDD.DDD";"Maximum frequency, Hz:",Fmax
9690     PRINT
9700     L1$="Percent change in shear modulus per degree C:  "
9710     L2$="Percent change in Young's modulus per degree C:"
9720     L3$="Two point max-min approach:"
9730     L4$="Multi-point least-squares approach:"
9740     SELECT UPC$(Block3$)
9750       CASE "TORSIONAL"
9760         Gmin=Scale_gtor_min
9770         Gmax=Scale_gtor_max
9780         PRINT USING "3X,30A,ZZ,5X,D.DDD";"Minimum "&C4a$,Power,Gmin
9790         PRINT USING "3X,30A,ZZ,5X,D.DDD";"Maximum "&C4a$,Power,Gmax
9800         PRINT USING "3/,#"              ! Three more line feeds
9810         PRINT L1$
9820         PRINT
9830         PRINT USING "3X,27A,8X,DDD.DDD";L3$,Prcnt_per_c_2pt
9840         PRINT USING "3X,35A,DDD.DDD";L4$,Prcnt_per_c_ls
9850       CASE "FLEXURAL"
9860         Emin=Scale_eflex_min
9870         Emax=Scale_eflex_max
9880         PRINT USING "3X,30A,ZZ,5X,D.DDD";"Minimum "&C4b$,Power,Emin
9890         PRINT USING "3X,30A,ZZ,5X,D.DDD";"Maximum "&C4b$,Power,Emax
9900         PRINT USING "3/,#"              ! Three more line feeds
9910         PRINT L2$
9920         PRINT
9930         PRINT USING "3X,27A,8X,DDD.DDD";L3$,Prcnt_per_c_2pt
9940         PRINT USING "3X,35A,DDD.DDD";L4$,Prcnt_per_c_ls
9950       CASE "LONGITUDINAL"
9960         Emin=Scale_elong_min
9970         Emax=Scale_elong_max
9980         PRINT USING "3X,32A,ZZ,5X,D.DDD";"Minimum "&C4b$,Power,Emin
9990         PRINT USING "3X,32A,ZZ,5X,D.DDD";"Maximum "&C4b$,Power,Emax
10000        PRINT USING "3/,#"              ! Three more line feeds
10010        PRINT L2$
10020        PRINT
10030        PRINT USING "3X,27A,8X,DDD.DDD";L3$,Prcnt_per_c_2pt
```

```
10040         PRINT USING "3X,35A,DDD.DDD";L4$,Prcnt_per_c_ls
10050       END SELECT
10060       PRINT Formfeed$                  ! Advance to top of next page
10070       PRINTER IS CRT
10080       RETURN
10090!*********************************************************************
10100 Freq_time:! Produces frequency vs time graph w/curve
10110!*********************************************************************
10120       GOSUB Draw_freq_time
10130       CALL Generic_curve(Pen3,Time(*),Resfreq(*),20*Arg1)
10140       RETURN
10150!*********************************************************************
10160 Output_device: ! Permits user to route graphs to the screen or plotter
10170!*********************************************************************
10180       OUTPUT KBD;Clear$;                          ! Clear the CRT
10190       OUTPUT KBD;Home$;                             ! Home display
10200       GRAPHICS OFF                   ! Turn off the graphics display
10210       SELECT Plot_device$
10220         CASE <>"Plotter"
10230           INPUT "Graphs appear on the screen, OK? (Y/N) ",Response$
10240           IF UPC$(Response$)<>"Y" THEN
10250             Plot_device$="Plotter"
10260             DISP "Graphs will be sent to the Plotter"
10270           ELSE
10280             DISP "Graphs will remain on the screen"
10290             WAIT 1
10300             DISP
10310             GRAPHICS ON
10320           END IF
10330         CASE "Plotter"
10340           INPUT "Graphs are sent to the plotter, OK? (Y/N) ",Response$
10350           IF UPC$(Response$)<>"Y" THEN
10360             Plot_device$="Screen"
10370             DISP "Plots will be sent to the Screen"
10380           ELSE
10390             DISP "Plots will stay routed to the plotter"
10400           END IF
10410       END SELECT
10420       WAIT 1
10430       DISP
10440       RETURN
10450!*********************************************************************
10460 Xscale_option: ! Permits user to auto scale or manual scale the X axis
10470!*********************************************************************
10480       OUTPUT KBD;Clear$;                          ! Clear the CRT
10490       OUTPUT KBD;Home$;                             ! Home display
10500       GRAPHICS OFF                   ! Turn off the graphics display
10510       SELECT Xscale$
10520         CASE "Auto scale X"
10530           INPUT "X axis is automatically scaled, OK? (Y/N) ",Response$
10540           IF Response$<>"Y" THEN
```

```
10550             Xscale$="User scale X"
10560             INPUT "Minimum X axis value ?",Xmin_manual
10570             INPUT "Maximum X axis value ?",Xmax_manual
10580             INPUT "Major X axis increment ?",Xmajor_manual
10590             INPUT "Minor X axis increment ?",Xminor_manual
10600             DISP "The X axis will be scaled manually"
10610           ELSE
10620             DISP "The X axis will remain auto scaled"
10630             WAIT 1
10640             DISP
10650             GRAPHICS ON
10660           END IF
10670         CASE "User scale X"
10680           INPUT "X axis is manually scaled, OK? (Y/N) ",Response$
10690           IF Response$<>"Y" THEN
10700             Xscale$="Auto scale X"
10710             DISP "The X axis will be scaled automatically"
10720           ELSE
10730             INPUT "Change manual limits ? (Y/N) ",Response$
10740             IF Response$="Y" THEN
10750               INPUT "Minimum X axis value ?",Xmin_manual
10760               INPUT "Maximum X axis value ?",Xmax_manual
10770               INPUT "Major X axis increment ?",Xmajor_manual
10780               INPUT "Minor X axis increment ?",Xminor_manual
10790               DISP "The X axis will be scaled with new values"
10800             ELSE
10810               DISP "The X axis will remain manually scaled"
10820               WAIT 1
10830               DISP
10840               GRAPHICS ON
10850             END IF
10860           END IF
10870       END SELECT
10880       WAIT 1
10890       DISP
10900       RETURN
10910!*****************************************************************
10920 Yscale_option: ! Permits user to auto scale or manual scale the Y axis
10930!*****************************************************************
10940       OUTPUT KBD;Clear$;                          ! Clear the CRT
10950       OUTPUT KBD;Home$;                           ! Home display
10960       GRAPHICS OFF                     ! Turn off the graphics display
10970       SELECT Yscale$
10980         CASE "Auto scale Y"
10990           INPUT "Y axis is automatically scaled, OK? (Y/N) ",Response$
11000           IF Response$<>"Y" THEN
11010             Yscale$="User scale Y"
11020             INPUT "Minimum Y axis value ?",Ymin_manual
11030             INPUT "Maximum Y axis value ?",Ymax_manual
11040             INPUT "Major Y axis increment ?",Ymajor_manual
11050             INPUT "Minor Y axis increment ?",Yminor_manual
```

```
11060             DISP "The Y axis will be scaled manually"
11070           ELSE
11080             DISP "The Y axis will remain auto scaled"
11090             WAIT 1
11100             DISP
11110             GRAPHICS ON
11120           END IF
11130         CASE "User scale Y"
11140           INPUT "Y axis is manually scaled, OK? (Y/N) ",Response$
11150           IF Response$<>"Y" THEN
11160             Yscale$="Auto scale Y"
11170             DISP "The Y axis will be scaled automatically"
11180           ELSE
11190             INPUT "Change manual limits ? (Y/N) ",Response$
11200             IF Response$="Y" THEN
11210               INPUT "Minimum Y axis value ?",Ymin_manual
11220               INPUT "Maximum Y axis value ?",Ymax_manual
11230               INPUT "Major Y axis increment ?",Ymajor_manual
11240               INPUT "Minor Y axis increment ?",Yminor_manual
11250               DISP "The Y axis will be scaled with new values"
11260             ELSE
11270               DISP "The Y axis will remain manually scaled"
11280               WAIT 1
11290               DISP
11300               GRAPHICS ON
11310             END IF
11320         END IF
11330       END SELECT
11340       WAIT 1
11350       DISP
11360       RETURN
11370!****************************************************************
11380 Temp_time: ! Produces Temperature vs Time graph w/curve
11390!****************************************************************
11400       Main_title$=Label$(7)
11410       Sub_title$=Label$(8)
11420       X_axis_name$=Label$(3)
11430       Y_axis_name$=Label$(5)
11440       Xmin=0                    ! Minimum time is 0 hours
11450       Xmax=20                   ! Maximum time is 20 hours
11460       Ymin=Actual_temp_min          ! Actual minimum temperature
11470       Ymax=Actual_temp_max          ! Actual maximum temperature
11480       GOSUB Generic_plot
11490       CALL Generic_curve(Pen3,Time(*),Thermistor(*),20*Arg1)
11500       RETURN
11510!****************************************************************
11520 Freq_temp: ! Produces Frequency versus temperature graph w/curve
11530!****************************************************************
11540       Main_title$=Label$(6)
11550       Sub_title$=""
11560       X_axis_name$=Label$(5)
```

```
11570      Y_axis_name$=Label$(4)
11580      Xmin=Actual_temp_min              ! Actual minimum temperature
11590      Xmax=Actual_temp_max              ! Actual maximum temperature
11600      Ymin=Actual_freq_min              ! Actual minimum frequency
11610      Ymax=Actual_freq_max              ! Actual maximum frequency
11620      GOSUB Generic_plot
11630      CALL Generic_curve(Pen3,Thermistor(*),Resfreq(*),20*Arg1)
11640!      PEN Pen4
11650!     MOVE Actual_temp_min,Actual_temp_min*Slope+Intercept
11660!     DRAW Actual_temp_max,Actual_temp_max*Slope+Intercept
11670!      PEN 0
11680      RETURN
11690!****************************************************************
11700 Create_new_file: !  Creates a file for a new data run
11710!****************************************************************
11720      Pass$="Initial"
11730      Grid_type$=Default_grid$
11740      Xscale$="User scale X"
11750      Yscale$="User scale Y"
11760      Plot_device$="Screen"
11770       BEEP 1000,.1
11780      ON ERROR GOTO Fix2
11790        INPUT "Filename to store the data ?",Filename$
11800        CREATE BDAT Filename$,50
11810        ASSIGN @Path_1 TO Filename$
11820      OFF ERROR
11830      OUTPUT @Path_1;Block1$,Block2$,Block3$,Block4$
11840      OUTPUT @Path_1;Mass,Length,Diameter,Density
11850       BEEP 1000,.1
11860      DISP "Output will be stored under Filename: ";Filename$
11870      WAIT 1
11880      DISP
11890      IF Flag=1 THEN
11900        FOR I=0 TO 20*Arg1
11910            OUTPUT @Path_1;Mod(I),Thermistor(I),Resfreq(I),Inphmag(I),
Redfreq(I)
11920        NEXT I
11930      END IF
11940      RETURN
11950!****************************************************************
11960 Open_old_file: ! Opens and retrieves data from an existing file
11970!****************************************************************
11980       Pass$="Follow on"
11990      Grid_type$=Default_grid$
12000      Xscale$="Auto scale X"
12010      Yscale$="Auto scale Y"
12020      Plot_device$="Screen"
12030       BEEP 1000,.1
12040      ON ERROR GOTO Fix1
12050        INPUT "Filename to retrieve the data ?",Filename$
12060        ASSIGN @Path_1 TO Filename$
```

```
12070        ENTER @Path_1;Block1$,Block2$,Block3$,Block4$
12080        ENTER @Path_1;Mass,Length,Diameter,Density
12090        BEEP 1000,.1
12100        DISP "Retrieving data stored under Filename: ";Filename$
12110        FOR I=0 TO 20*Arg1
12120           ENTER @Path_1;Mod(I),Thermistor(I),Resfreq(I),Inphmag(I),Red
freq(I)
12130           Time(I)=I/Arg1
12140        NEXT I
12150      OFF ERROR
12160      ASSIGN @Path_1 TO *
12170      RETURN
12180!*******************************************************************
12190 Fix1: !
12200!*******************************************************************
12210      SELECT ERRN
12220      CASE 53
12230        DISP "Limit file names to 10 characters. No punctuation."
12240      CASE 56
12250        DISP "This file doesn't exist on the data disk"
12260      CASE 58
12270        DISP "This file is not a BDAT file"
12280      CASE ELSE
12290        DISP " This file can not be processed by RT20B"
12300      END SELECT
12310      PRINTER IS CRT
12320       BEEP 300,.1
12330      WAIT 1
12340      DISP
12350      WAIT 1
12360      GOTO Open_old_file
12370!*******************************************************************
12380 Fix2: !
12390!*******************************************************************
12400      SELECT ERRN
12410      CASE 53
12420        DISP "Limit file names to 10 characters. No punctuation."
12430      CASE 54
12440        DISP "Duplicate filename! Try another name."
12450      END SELECT
12460       BEEP 300,.1
12470      WAIT 1
12480      DISP
12490      WAIT 1
12500      GOTO Create_new_file
12510!*******************************************************************
12520 Close_file: ! Closes new data file after data collection is completed
12530!*******************************************************************
12540      GCLEAR
12550      ASSIGN @Path_1 TO *
12560       BEEP 1000,.1
```

```
12570     DISP "Data is stored under Filename: ";Filename$
12580     WAIT 1
12590     DISP
12600     RETURN
12610!**************************************************************
12620 Program_end:  ! Shuts down shop, plays a little melody
12630!**************************************************************
12640      OUTPUT KBD;Clear$;
12650      GRAPHICS OFF
12660      CONTROL 1,12;0
12670       BEEP 157,.1
12680       BEEP 201,.1
12690       BEEP 178,.1
12700       BEEP 272,.1
12710      WAIT .5
12720       BEEP 272,.1
12730       BEEP 178,.1
12740       BEEP 157,.1
12750       BEEP 201,.1
12760      DISP
12770       DISP "Press RUN when you are ready for another try ...."
12780      END
12790!**************************************************************
12800 SUB Label(Csize,Asp_ratio,Ldir,Lorg,Pen,Xpos,Ypos,Text$)
12810!**************************************************************
12820!   This subroutine defines several systems variables (Csize, LDIR, etc.),
12830!   and labels the text (if any) accordingly.
12840    DEG
12850    CSIZE Csize,Asp_ratio
12860    LDIR Ldir
12870    LORG Lorg
12880    PEN Pen
12890    MOVE Xpos,Ypos
12900    IF Text$<>"" THEN LABEL USING "#,K";Text$
12910    PENUP
12920    SUBEND
12930!**************************************************************
12940 SUB Lbl_axes(Csize,Asp_ratio,Pen,Xmin,Xmax,Xstep,Ymin,Ymax,Ystep)
12950!**************************************************************
12960    DEG
12970    CSIZE Csize,Asp_ratio
12980    PEN Pen
12990    CLIP OFF
13000    LDIR 0
13010    LORG 6
13020    Yrange=Ymax-Ymin
13030    Yoffset=.02*Yrange
13040    FOR L=Xmin TO Xmax STEP Xstep
13050       MOVE L,Ymin-Yoffset
13060       IF ABS(L)<.001 THEN L=0
13070       LABEL USING "#,K";L
```

```
13080   NEXT L
13090   LORG 8
13100   Xoffset=.02*(Xmax-Xmin)
13110   IF Yrange<=1 THEN
13120     Mmax=DROUND(Yrange/Ystep,1)
13130     Yval=Ymin
13140     FOR M=0 TO Mmax
13150        IF ABS(Yval)<=.001 THEN Yval=0
13160        MOVE Xmin-Xoffset,Yval
13170        LABEL USING "#,SD.DD";Yval
13180        Yval=Yval+Ystep
13190     NEXT M
13200   ELSE
13210     FOR M=Ymin TO Ymax STEP Ystep
13220        IF ABS(M)<=.001 THEN M=0
13230        MOVE Xmin-Xoffset,M
13240         LABEL USING "#,K";M
13250     NEXT M
13260   END IF
13270   CLIP ON
13280   PENUP
13290   SUBEND
13300!*****************************************************************
13310 SUB Block_info(Block1$,Block2$,Block3$,Block4$,Xgdumax,Pen,Pen2)
13320!*****************************************************************
13330    CALL Label(3,.6,0,2,Pen,2,2,"Rod: "&Block1$)
13340    CALL Label(3,.6,0,5,Pen,Xgdumax/3,2,"Run: "&Block2$)
13350    CALL Label(3,.6,0,5,Pen,Xgdumax*2/3,2,"Mode: "&Block3$)
13360    CALL Label(3,.6,0,8,Pen,.97*Xgdumax,2,Block4$)
13370   MOVE 0,4
13380   PEN Pen2
13390   DRAW 133,4
13400   PENUP
13410   SUBEND
13420!*****************************************************************
13430 SUB Least_squares(Imax,X(*),Y(*),Slp,Int,Cor,Slp_er,Int_er,Xmean,Ymean)
13440!*****************************************************************
13450    DISP "Computing least-squares fit ........."
13460   Sumx=0
13470   Sumy=0
13480   Sumxx=0
13490   Sumxy=0
13500   FOR I=0 TO Imax
13510      Sumx=Sumx+X(I)
13520      Sumxx=Sumxx+X(I)^2
13530      Sumy=Sumy+Y(I)
13540      Sumxy=Sumxy+X(I)*Y(I)
13550   NEXT I
13560   Delta=(Imax+1)*Sumxx-Sumx^2
13570   Int=(Sumxx*Sumy-Sumx*Sumxy)/Delta
13580   Slp=((Imax+1)*Sumxy-Sumx*Sumy)/Delta
```

```
13590    Sumerrerr=0
13600    FOR J=0 TO Imax
13610        Sumerrerr=Sumerrerr+(Y(J)-Int-Slp*X(J))^2
13620    NEXT J
13630    Sigmayy=Sumerrerr/(Imax+1-2)
13640    Sigmay=SQR(Sigmayy)
13650    Int_er=Sigmay*SQR(Sumxx/Delta)
13660    Slp_er=Sigmay*SQR((Imax+1)/Delta)
13670    Xbarsum=0
13680    Ybarsum=0
13690    FOR K=0 TO Imax
13700       Xbarsum=Xbarsum+X(K)
13710       Ybarsum=Ybarsum+Y(K)
13720    NEXT K
13730    Xmean=Xbarsum/(Imax+1)
13740    Ymean=Ybarsum/(Imax+1)
13750    Sigmaxxsum=0
13760    Sigmayysum=0
13770    Sigmaxysum=0
13780    FOR L=O TO Imax
13790       Sigmaxxsum=Sigmaxxsum+(X(L)-Xmean)^2
13800       Sigmayysum=Sigmayysum+(Y(L)-Ymean)^2
13810       Sigmaxysum=Sigmaxysum+(X(L)-Xmean)*(Y(L)-Ymean)
13820    NEXT L
13830    Sigmax=SQR(Sigmaxxsum/(Imax+1))
13840    Sigmay1=SQR(Sigmayysum/(Imax+1))
13850    Sigmaxy=Sigmaxysum/(Imax+1)
13860    Cor=Sigmaxy/(Sigmax*Sigmay1)
13870    DISP
13880    SUBEND
13890!*****************************************************************
13900 SUB Scale(L,R,B,T,Top,Left,Xcenter,Ycenter,Xgdumax,Ygdumax)
13910!*****************************************************************
13920    Top=T*Ygdumax
13930    Bottom=B*Ygdumax
13940    Left=L*Xgdumax
13950    Right=R*Xgdumax
13960    Xcenter=(Right+Left)/2
13970    Ycenter=(Top+Bottom)/2
13980    VIEWPORT Left,Right,Bottom,Top
13990    SUBEND
14000!*****************************************************************
14010 SUB Yscale(Ymin,Ymax,Yminor,Ymajor)
14020!*****************************************************************
14030    DIM Diff(36),Minor(36)
14040       DATA   .1,.005,.2,.01,.25,.01,.3,.02,.4,.02,.5,.02,.75,.05,1,.05
14050       DATA 5,.2,10,.5,15,1,20,1,25,1,30,2,40,2,50,2,75,5,100,5,125,5
14060      DATA 150,10,200,10,250,10,300,20,400,20,500,20,750,50,1000,50
14070      DATA 1250,50,1500,100,2000,100,2500,100,3000,200,4000,200,5000
14080     DATA 200,7500,500,10000,500
14090    FOR I=1 TO 36
```

```
14100      READ Diff(I),Minor(I)
14110    NEXT I
14120    Yrange=Ymax-Ymin
14130    Index=1
14140    WHILE Yrange>Diff(Index)
14150      Index=Index+1
14160    END WHILE
14170    Yminor=Minor(Index)
14180    Ymajor=Diff(Index)/5
14190    IF Ymin<0 THEN
14200      Newmin=Ymin-Ymajor+ABS(Ymin MOD Ymajor)
14210    ELSE
14220      Newmin=Ymin-(Ymin MOD Ymajor)
14230    END IF
14240    Newmax=Newmin+Diff(Index)
14250    WHILE Ymax>Newmax
14260      Index=Index+1
14270      Yminor=Minor(Index)
14280      Ymajor=Diff(Index)/5
14290      IF Ymin<0 THEN
14300        Newmin=Ymin-Ymajor+ABS(Ymin MOD Ymajor)
14310      ELSE
14320        Newmin=Ymin-(Ymin MOD Ymajor)
14330      END IF
14340      Newmax=Newmin+Diff(Index)
14350    END WHILE
14360    Ymax=Newmax
14370    Ymin=Newmin
14380    SUBEND
14390!******************************************************************
14400 SUB Xscale(Xmin,Xmax,Xminor,Xmajor)
14410!******************************************************************
14420    DIM Diffx(40),Minorx(40),Majorx(40)
14430       DATA  5.,0.2,1.0,6.,.2,1.,7.0,0.2,1.0,8.0,0.2,1.0,10.0,0.5,2.0,12.0,0.5
14440       DATA  2.0,14.0,0.5,2.0,16.0,0.5,2.0,20.0,1.0,4.0,25.0,1.0,5.0,30.0,1.0
14450       DATA  5.0,35.0,1.0,5.0,40.0,1.0,5.0,50.0,2.0,10.0,60.,2.0,10.0,70.0,2.0
14460      DATA  10.0,80.0,2.0,10.0,100.0,5.0,20.0,120.0,5.0,20.0,140.0,5.0,20.0
14470      DATA  200.0,10.0,20.0,400.0,10.0,50.0,600.0,20.0,100.0,800.0,50.0,100.0
14480     DATA  1000.0,50.0,100.0,1200.0,50.0,200.0,1400.0,50.0,200.0,1600.0
14490     DATA  50.0,200.0,1800.0,100.0,300.0,2000.0,100.0,500.0,2500.,100.,500.0
14500     DATA  3000.,100.,500.0,3500.,100.,500.0,4000.,200.,400.0
14510    FOR I=1 TO 34
14520      READ Diffx(I),Minorx(I),Majorx(I)
14530    NEXT I
14540    Xrange=Xmax-Xmin
14550    Index=1
14560    WHILE Xrange>Diffx(Index)
14570      Index=Index+1
14580    END WHILE
14590    Xminor=Minorx(Index)
14600    Xmajor=Majorx(Index)
```

```
14610    IF Xmin<0 THEN
14620      Newmin=Xmin-Xmajor+ABS(Xmin MOD Xmajor)
14630    ELSE
14640      Newmin=Xmin-(Xmin MOD Xmajor)
14650    END IF
14660    Newmax=Newmin+Diffx(Index)
14670    WHILE Xmax>Newmax
14680      Index=Index+1
14690      Xminor=Minorx(Index)
14700      Xmajor=Majorx(Index)
14710      IF Xmin<0 THEN
14720        Newmin=Xmin-Xmajor+ABS(Xmin MOD Xmajor)
14730      ELSE
14740        Newmin=Xmin-(Xmin MOD Xmajor)
14750      END IF
14760      Newmax=Newmin+Diffx(Index)
14770    END WHILE
14780    Xmax=Newmax
14790    Xmin=Newmin
14800    SUBEND
14810!*****************************************************************
14820 SUB Generic_curve(Pen,X(*),Y(*),Max_point)
14830!*****************************************************************
14840    PEN Pen
14850    FOR Point=0 TO Max_point
14860      PLOT X(Point),Y(Point)
14870    NEXT Point
14880    PENUP
14890    SUBEND
14900!*****************************************************************
14910! Nothing follows.
14920!*****************************************************************
14930!*****************************************************************
14940!*****************************************************************
14950 SUB Calc_redfreq(Imax,Thermistor(*),Resfreq(*),Redfreq(*))
14960!*****************************************************************
14970    FOR I=0 TO Imax
14980      Temp(I)=Thermistor(I)+273.15
14990      X(I)=-129*(Temp(I)-283.15)/(107+Temp(I)-283.15)
15000      Y(I)=X(I)*LOG(10)
15010      Alphat(I)=EXP(Y(I))
15020      Redfreq(I)=Resfreq(I)*Alphat(I)
15030    NEXT I
15040    SUBEND
```

APPENDIX E. LISTING OF HP BDAT FILE TO MACINTOSH TEXT FILE CONVERSION PROGRAM

```
10 PRINTER IS CRT;WIDTH 80
20 PRINT "***********************************************************"
30 PRINT "*PROGRAM HPTOMAC: Program to transfer BDAT files on the HP to"
40 PRINT "TEXT files readable by Cricket Graph on the Macintosh."
50 PRINT "Ref. pp. C-6 and C-17 of the Cricket Graph User's Manual."
60 PRINT "Author: Steve Baker   Last revision date: 10 Aug 1989"
70 PRINT "*HARDWARE REQUIRED: HP Series 200 with 98644A serial interface or"
80 PRINT "Series 300 with built-in interface, Macintosh with built-in serial"
90 PRINT "interface, Hayes modem cable for the Macintosh (DB-9 or Din-8 to"
100 PRINT "male DB-25 connectors. Ref. p.G-5 of the VersaTerm Pro User's"
110 PRINT "Manual), standard male-male RS-232 cable with at least pins 1-8"
120 PRINT "and 20 wired straight through for the HP. These cables can each"
130 PRINT "be hooked up directly to a modem, or they can be connected to each"
140 PRINT "other through a null modem with the following pins connected:"
150 PRINT "1to1, 2to3, 3to2, 4and5to8, 6to20, 7to7, 8to4and5, 20to6."
160 PRINT "*SOFTWARE REQUIRED: HPTOMAC running on an HP Series 200/300 and a"
170 PRINT "communications program capable of faithfully capturing incoming"
180 PRINT "text (ASCII characters) to a TEXT-type file running on the Mac,"
190 PRINT "such as MacTerm (desk accessory bundled with Borland SideKick) or"
200 PRINT "VersaTerm PRO. NOTE: text captured by Microsoft Works cannot be"
210 PRINT "read by Cricket Graph."
220 PRINT "*INSTRUCTIONS FOR USE:"
230 PRINT "Both serial ports must be set to 2400 baud, 8 data bits, one stop"
240 PRINT "bit, no parity. The following will correctly set up both machines"
250 PRINT "following power-up."
260 PRINT "*SETTING UP THE HP: HPTOMAC asks for the select code of the"
270 PRINT "serial port and sets the baud rate to 2400 baud. The other"
280 PRINT "settings are automatic at startup, so no additional user action is"
290 PRINT "required (Ref. p. 13-10 of Vol.2 of BASIC Interfacing Techniques)."
300 PRINT "*SETTING UP MACTERM: launch the ""Configure MacTerm"" utility and"
310 PRINT "click on the appropriate buttons to set serial port parameters"
320 PRINT "(Ref. p. 107 of SideKick v2.0 User's Manual). Clicking on ""Save"
330 PRINT "Setup"" saves these settings. The serial port parameters may also"
340 PRINT "be set in the ""MacTerm"" menu while running MacTerm (MacTerm is"
350 PRINT "launched from the desk accessory menu)."
360 PRINT "*SETTING UP VERSATERM PRO: Launch VersaTerm PRO. Set the baud"
370 PRINT "rate to 2400 in the ""Baud"" menu. Enable Xon/Xoff, set Parity to"
380 PRINT "none, Char Size to 8 bits, and Stop Bits to 1.0 in the"
390 PRINT """Settings"" menu. Other features may be enabled and disabled in"
400 PRINT "the ""Extras"" dialog box, selected from the ""Settings"" menu"
410 PRINT "(Ref. pp. F-15 to F-18 of the User's Manual). Be sure that ""Auto"
420 PRINT "Tek 4014 Entry"" is disabled."
430 PRINT "*TRANSFERRING A BDAT FILE from the HP to the Mac is accomplished"
440 PRINT "in text recording mode under MacTerm (ref. p. 109 in User's"
450 PRINT "Manual) and in Save Stream mode under VersaTerm PRO (ref. pp."
460 PRINT "B-28, F-8, F-13, F-15 in the User's Manual). Refer to each User's"
```

```
470  PRINT "Manual for details.  HPTOMAC is self-prompting."
480  PRINT "*NOTE that PROG files may also be transferred over the serial port"
490  PRINT "connection simply by LOADing each PROG file into the HP's memory"
500  PRINT "and issuing a LIST #Sc command, where Sc is the select code of the"
510  PRINT "serial port.  The setup and procedure for receiving a PROG file"
520  PRINT "under MacTerm or VersaTerm PRO is identical to that for receiving"
530  PRINT "a BDAT file."
540  PRINT "************************************************************"
550  !
560  !*****PROGRAM BEGINS HERE*************************************
570  !
580  DIM Ch$[1],Name$(100)[31]
581   DIM C1$[50],C2$[50],C3$[50],C4$[50]
590  INTEGER Outdev,I,N
600   PRINT "PROGRAM HPTOMAC:  Program to transfer BDAT files on the HP to
TEXT"
610  PRINT "files readable by Cricket Graph on the Macintosh.  Detailed"
620  PRINT "instructions for using this program are in the comments above."
630  BEEP
640  PRINT
650  PRINT "***** MAKE SURE THE MAC SERIAL PORT IS SET TO 2400 BAUD,
8 DATA"
660  PRINT "BITS, 1 STOP BIT, NO PARITY *****"
670  PRINT
680  MASS STORAGE IS ":,4,0"
690  PRINT "Mass storage default has been set to :,4,0"
700  INPUT "Enter select code of output device (CRT=1, PRT=701, Serial Port=9 o
r 10):",Outdev
710  IF Outdev=9 OR Outdev=10 THEN CONTROL Outdev,3;2400
720  INPUT "Enter name of source data file:",Srcfile$
730  ASSIGN @Path1 TO Srcfile$
740  INPUT "Enter number of elements per record (1 to 100):",N
750  IF N<1 OR N>100 THEN GOTO 740
760  INPUT "Do you want to send element names? (Y or N, default is N)",Ch$
770  IF Ch$="Y" OR Ch$="y" THEN
780    Ch$="Y"
790    FOR I=1 TO N
800      PRINT "Enter name of ";I;"th element:"
810      LINPUT Name$(I)
820    NEXT I
830  END IF
840  INPUT "Hit CONTINUE to continue",Ch$
850  PRINT
860  PRINT "Sending output to device select code ";Outdev
870  PRINTER IS Outdev;WIDTH OFF
880  IF Ch$="Y" THEN
890    PRINT "*"
900    FOR I=1 TO N-1
910      PRINT Name$(I);CHR$(9);
920    NEXT I
930    PRINT Name$(N)
```

```
940  END IF
950  ON END @Path1 GOTO 1040
951  ENTER @Path1;C1$,C2$,C3$,C4$
952  ENTER @Path1;Mass,Length,Diameter,Density
960  REPEAT
970    FOR I=1 TO N-1
980      ENTER @Path1;Data
990      PRINT Data;CHR$(9);
1000    NEXT I
1010    ENTER @Path1;Data
1020    PRINT Data
1030  UNTIL False
1040  OFF END @Path1
1050  ASSIGN @Path1 TO *
1060  BEEP
1070  PRINTER IS CRT;WIDTH 80
1080  PRINT "Transfer complete.  Close Mac file."
1090  PRINT "Open new Mac file and enter HP source file name to transfer"
1100  INPUT "another file with the same attributes or hit RUN to restart:",Srcfi
le$
1110  ASSIGN @Path1 TO Srcfile$
1120  GOTO 840
1130  END
```

LIST OF REFERENCES

1. Van Vlack, L. H., *Materials Science for Engineers*, Addison-Wesley, 1970.

2. American Society for Testing and Materials, D 2231-87, Vol 09.01, *Standard Practice for Rubber Properties in Forced Vibration*, 1987.

3. Garrett, S. L., "Resonant acoustic determination of elastic moduli," *J.Acoust. Soc. Am.*, Vol 88(1), pp.210-221, July 1990.

4. Mechanical Measurement Devices, P.O. Box 8716, CA 93943.

5. Barone, A., and Giacomini, A., "Experiments on some electrodynamic ultrasonic vibrators," *Acoustica*, Vol 4, pp.182-184, 1954.

6. Wetterskog, K., Beaton, B. L., and Serocki, J., *A Fiber-optic Acceleration Canceling Hydrophone Made of a Castable Epoxy*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1990. [DTIC AD - B146 067]

7. Kinsler, L. E., Frey, A. R., Coppens, A. B., and Sanders, J. V., *Fundamentals of Acoustics*, 3rd ed., John Wiley & Sons., 1982.

8. Elamore, W. C., and Heald, M. A., *Physics of Waves*, Dover Publications,Inc., 1985.

9. Landau, L. D., and Lifshitz, E. M., *Theory of Elasticity*, Section 25, Pergamon Press, 1970.

10. Ferry, J. D., *Viscoelastic Properties of Polymers*, 2nd ed., John Wiley & Sons, Inc., 1970.

11. Bland, D. R., *The Theory of Linear Viscoelasticity*, pp. 114-115, Pergamon Press, 1960.

12. Rudnick, I., "Zero sound and the viscoelasticity of liquid ^{3}He," *J. Low Temp. Phys.*, Vol. **40**, Nos. 3/4, pp. 287-296, 1980.

13. Swift, G. W.,"Thermoacoustic engines," *J. Acoust. Soc. Am.*, Vol 84(4), pp. 1145-1180, October 1988.

14. Ungar, E. E., and Hatch, D. K., " Your selection guide to high-damping materials," *Prod. Eng.*, pp.44-56, April 1961.

15. Williams, M. L., Landel, R. F., and Ferry, J. D., "The temperature dependence of relaxation mechanisms in amorphous polymers and other glass-forming liquids," *J. Amer. Chem. Soc.*, Vol 77, pp. 3701-3707, 1955.

16. Naval Research Laboratory, USRD Doc.# 61153-N, *Elastomeric Materials for Acoustical Applications*, by Rodger N. Capps, 15 September 1989.

17 Lagakos, N., and others, "Planar flexible fiber-optic acoustic sensor," *J. Lightwave Tech.*, Vol 8(9), pp. 1298-1303, September 1990.

INITIAL DISTRIBUTION LIST

	No. Copies
1. Defense Technical Information Center Cameron Station Alexandria, VA 22304-6145	2
2. Library, Code 52 Naval Postgraduate School Monterey, CA 93943-5100	2
3. Physics Department ATTN: Dr. S. L. Garrett Code PH/Gx Naval Postgraduate School Monterey, CA 93943	3
4. Physics Department ATTN: Mr. D. A. Brown Code PH/Brown Naval Postgraduate School Monterey, CA 93943	3
5. Physics Department ATTN: Dr. D. L. Gardner Code PH/Gardner Naval Postgraduate School Monterey, CA 93943	1
6. Commanding Officer Naval Sea Systems Command ATTN: R. Supersano - Code 06UR4 Washington, D.C. 20362-5101	1
7. Underwater Sound Reference Detachment Naval Research Laboratory ATTN: Dr. R. N. Capps Code 5975 P.O. Box 568337 Orlando, FL 32856-8337	1
8. Naval Logistics Department, HQ RSN ATTN: Mr. Tan Beng Hock MINDEF Building Gombak Drive SINGAPORE (2366)	2

Thesis
T13563 Tan
c.1 Resonant acoustic determination of complex elastic moduli.